MSc Program
Renewable Energy in Central and Eastern Europe

Fuel Cell and Hydrogen

Residential Fuel Cell supplying Energy for Heat, Electricity and Transportation using Hydrogen produced from excess photovoltaic primary energy

An energetic, ecological and economic analysis

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
Dipl.-Ing. Dr. Amela Ajanovic

Mortimer Schulz, BA
Student ID 1127413

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Affidavit

I, Mortimer Edgar Schulz, hereby declare

1. that I am the sole author of the present Master's Thesis, "Fuel Cell and Hydrogen", 99 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and

2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

This master's thesis is an analysis of the residential fuel cell using hydrogen as fuel.

The concept of storing energy obtained from renewable sources is growing more popular, whether on broad scale or smaller scale. It is tied to considerable investments, but once it is operational and amortised, plants of renewable energy and energy storage feature low cost maintenance, and the actual source (Sun, wind, hydro) is yet for free.

Residential fuel cells range from 0.7 to 5 kW and have been implemented through national programmes and test phases carry on until 2015 and 2107 resp. This market may develop into a positive direction and spread to more countries. Whether only residential or also communal and commercial buildings may benefit, remains to be seen.

This master's thesis analyses the fuel cell from the energetic balance including electrochemical, thermodynamic and kinetic principles, for which an efficiency of 36% was calculated.
The ecological consideration has to be thrown into the overall equation, and it is found that while some raw materials are energy-intensive in the manufacturing process, such as graphite, other raw materials need to be transported long distances, such as platinum. The good news is that 50% of a fuel cell today can be recycled.
The economic argument stresses that service companies have demonstrated interest to finance the equipment by means of leasing arrangements with a monthly fee paid by the user.

A Case study is used to quantify the energy services demand of the single-family household lay with regard to heat, electricity and transportation. The latter is meant in the form of charging E-mobility on the premises, also a trend, and calculating this into the annual PV yield. The house in Tyrol requires 13 kW peak of photovoltaic with an annual yield of 14,600 kWh, calculated by an online tool of the European Union called PVIGS. An excess of 2,500 kWh p.a. is used to run an electrolyser during the Summer season to produce hydrogen which is stored, and used in Winter by the fuel cell to re-supply the energy

Foreword

In 1839 Alexandre-Edmond Becquerel of France experimented among others with platinum to be used as electrodes, when letting silver chloride react with an acidic solution inside a black box, and while exposed to sunlight. A so-called photovoltaic effect had occurred which produced a current; Sunlight (2013).

In the same year, Sir William Robert Grove of Wales immersed platinum foils in a sulphuric acid solution, and supplied hydrogen and oxygen to the foils that were set up in alternating order. The catalytic effect of the platinum allowed for the acid to transport the hydrogen protons and the electrons to produce a current. Hence, it was called a gas voltaic battery, today known as the fuel cell; FuelCell Today (2012).

In the 1950s research picked up considerably to develop further the photovoltaic as well as the fuel cell technology. In the latter case liquid electrolytes were replaced by solid membranes, which came to be known as polymer-exchange membranes (PEM) and made fuel cells more compact and easier to transport. Such a membrane was then also employed in the electrolyser, the device that splits the water into it's components hydrogen and oxygen. Since the 1980s electrolysis was being tested with the power derived from renewable energy sources, such as photovoltaic, wind and hydro power. The resulting hydrogen, a secondary energy carrier, can be stored as compressed gas in cylinders for longer time periods, and used by fuel cells to supply energy when needed.

These concepts have been tested in the residential sector, and, if energetic, ecological and economic arguments can be satisfactorily combined, then these systems are around the corner of the near future, as the storage of renewable energy today is a key dialogue.

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Abbreviations, acronyms

AC	alternative current
CHP / RHP	combined heat and power / residential heat and power
COP	coefficient of performance
DC	direct current
EPBD	Energy Performance Buildings Directive
ES	energy services
EU / EC	European Union / *European Community* or European Commission
FC	fuel cell
FE	final energy [also referred to as EE in other sources]
fGEE	Overall Energy Efficiency Factor
FIT	feed-in tariff
FP5	European Commission Fifth Framework Programme (1998 – 2002)
HDD	heating degree day
HHV	higher heating value
ISO	International Organisation for Standardization
LCA	Lifecycle Assessment
LHV	lower heating value
MP3	memory device, used for music downloading and listening
mio	million
PE	primary energy
PEM	proton-exchange membrane [fuel cell]
PV	photovoltaic
PVGIS	Photovoltaic Geographical Information System *(an online-PV calculation tool)*
SE	secondary energy
SOFC	solid-oxide fuel cells
UE	useful energy [also referred to as NE in other sources]
UK	United Kingdom
UNEP	United Nations Environmental Programme
WIFI	(Wifi / Wi-Fi) an apparatus wirelessly using radio waves such as the Internet
WLAN	wireless local-area-network; providing connection to radio waves
ZAMG	Central Institute for Meteorology & Geodynamics
ZSW	Zentrum für Sonnenenergie- und Wasserstoffforschung

Units, coefficients and variables

a	**a coefficient used by the Redlich-Kwong equation of state (0.42748)**
A	**1 Ampère = (1 Ampère-hour = 3,600 C)**
α_i / CRF	**Capital recovery factor**
b	**another coefficient used by the Redlich-Kwong equation of state (0.08664)**
C	**1 Coulomb = 6.24150965 x 10^{18} electrons or protons**
CH_2	**total investment and cost of a fuel cell during the major part of its lifetime (ca. 20 years)**
C_i	**total cost of a fuel cell with it's components C_{BE} , C_{BF}, C_{BS}**
Cs	**Heat capacity of water (in the storage tank)**
cm	**centimetres**
°C	**degree Celsius**
d	**day(s)**
Δ	**"change in/of …"**
ΔG	**"free" energy available to do work; according to Gibbs**
ΔH	**enthalpy of the reaction**
E°	**total voltage of the fuel cell**
E_{act}	**actual voltage**
η	**efficiency**
F	**1 Faraday = 94,485.3365 Coulombs**
g	**grams**
g/kW CO2	**grams per kilowatt of CO_2**
g/mol	**grams per mole**
H	**heat [H_f = final heat, H_i = initial heat]**
H^+	**hydrogen ion**
H_2	**hydrogen gas (g)**

H_2O	**water, (l) liquid resp. (g) vapour**
hPa	**hecto Pascal (100 Pa; 1 Pa = N/m²)**
I	**voltage current (I_{act} = actual, I_{max} = maximum)**
i	**current density / interest rate**
i_0	**exchange current density**
IC_j	**total investment**
j	**"density at the electrode" (j_{limit} = limit of the density at the electrode)**
J	**Joule (= kg x m² / s² = N x m = Pa x m³ = W x s = C x V)**
J/K	**Joules per Kelvin**
K	**Kelvin; 1 degree**
Kd	**Kelvin day(s)**
kJ	**kilo Joules**
kg	**Kilogram**
kg/m³	**kilogram per cubic-metre**
kg/s	**kilograms per second**
km	**kilometres**
km/h	**kilometres per hour**
kW el / kW_{el}	**kilowatt electric**
kWh / MWh	**kilowatt hours [th = thermal, el = electric] / megawatt hours**
kWh/kg	**kilowatt hours per kilogram**
kWh/m²/a	**kilowatt hours per square metre per year**
kWh/m³K	**kilowatt hours per cubic metre Kelvin**
kW th / kW_{th}	**kilowatt thermal**
l, l/day	**litre(s), litres per day**
λ	**relative concentration of O_2 in air**
ln	**natural log (2.718281828)**
m² / m³	**square-metres / cubic metres**
mio	**million**
mm	**millimetres**
mmHg	**millimetres mercury**
mol	**mole (6.0221367 x 10^{23} atoms; Avogadro's number)**
mol/s	**moles per second**
mV/K	**milli-Volt per Kelvin**
µ	**consumption**
N	**Newton (1N = 1kg x m/s²)**
n	**number of atoms resp. number of moles / number of years**
Nm³	**norm cubic metre (standard temperature and pressure, 25°C and 1 bar)**
O_2	**oxygen gas (g)**
P	**pressure of a gas**
P_C	**critical pressure**
PE	**Primary Energy**
P_{El}	**output electric**
%	**per cent**
pH	**„power of hydrogen";** *reciprocal activity of hydrogen ions in a solution*
O_2	**oxygen gas**
Qs	**heat capacity of the storage tank**
R	**ideal gas constant (8.3144621 J/mol K)**
r	**resistance**
rev	**reversible**
T	**temperature**
t	**time**
T_C	**critical temperature**
TΔS	**entropy of a reaction according to temperature of the environment**
th	**thermal**
Therm	**Thermodynamics**
V	**Volt**
V_{HHV}	**voltage at higher heating value of water, i.e. when in gaseous form (vapour)**
W	**Watt (1 Joule/second)**
W/m²K	Watts per square metre Kelvin determining heat loss resistance
z	**number of moles**

1. Introduction

This Section covers the motivation, the core objectives and structure of this paper.

1.1 Motivation

Recently the debate on energy storage has picked up with regard to renewable sources. Wind and Sun energy, though free of carbon emissions, fluctuate and cannot be timed. Therefore, different means have been researched and some are available on the market. For the residential sector, there are two types: accumulators (lithium-ions or lead gel) and hydrogen storage. In the latter case, hydrogen gas first has to be produced, but can then be stored for longer periods, such as six months, before being used by a fuel cell. In addition, for residences a buffer tank is also considered as storage in the form of heat.

Hydrogen and fuel cell technology, in the residential application to supply heat and power, is being tested in national programmes in Germany, “Callux” 2008-2015, in Japan, “Ene-farm” 2010-2015, and on a pan-European level, “Ene-field” 2012-2017. Their purpose is among others to increase the use of fuel cells and raise the awareness. Due to the fuel cell’s capability to produce heat, electricity and water, **primarily from renewable energy sources**, fuel cells offer a one-stop solution for residential, communal and commercial buildings, of various sizes, and including electric mobility.

The motivation to write this master’s thesis is to address the advantages of applying fuel cell technology in residential buildings, and find appropriate financing solutions for it.

1.2 Core objectives

This master’s thesis has the following four objectives:

a) A PEM fuel cell seen from the energetic input and output

To analyse the efficiency of a fuel cell of current technology in the residential application, and to analyse the life cycle of a fuel cell which includes the raw materials that went into production, as well as the recycling and disposal of it after the useful life.

b) Hydrogen to be produced from photovoltaic (PV) and then stored

To assess the energy chain starting with primary energy of the Sun, converted into electricity by the photovoltaic installation, including an inverter, and through the electrolysis process producing hydrogen as well as the storage of the hydrogen gas. Conversion losses and efficiency factors have to be taken into account at each step.

c) The energy demand of a single-family house covered by hydrogen and fuel cell
To quantify the total annual energy services demand of a household consisting of heat, electricity and transportation, in order to be able to dimension the photovoltaic installation that needs to cover this demand including related losses along the process.

d) Financing alternatives for residential fuel cells
As the technology is not yet widespread and economies of scale have not yet been realised, to identify possibilities of financing to help to increase the use of fuel cells.

1.3 Structure of the work

This master's thesis consists of nine Sections, including Introduction and Conclusion.

In order to analyse the residential fuel cell from energetic, ecological and economic perspectives, a case study of a single-family home provides the parametres as a basis to calculate. Section 2 briefly introduces this reference case and reviews the analytic models to be applied. Section 3 covers the fuel cell technology relevant to this master's thesis as well as aspects of hydrogen gas, such as production, storage and safety issues. The Case study is then described in Section 4 which consists of a single-family house. The information from Sections 2 to 4 will be used in the analyses in Sections 5 to 8.

In the energetic analysis in Section 5 the efficiency of the fuel cell will be assessed, as well as the efficiency of the entire system applied to the single-family home. Several model days will be applied to calculate the yield and the quantity of hydrogen produced. In Section 6 a shortened version of a life cycle assessment with the fuel cell as the functional unit will be reviewed to identify implications for the environment, and to understand the importance of the energy consumption before and after the useful life.
Section 7 is an economic assessment of the fuel cell applied in the Case study, identifying the investment and running cost, and finally proposing ways of financing.
The description of the economic, ecological and economic results is found in Section 8.

Finally conclusions will be offered in Section 9.

2. Description of method of approach applied

This Section first introduces the Case study briefly before going into more detail in Section 4. Then the models for the various analyses are being presented beginning with efficiency calculations to determine the energetic value, followed by the life cycle assessment as the ecological model, and finally the cost calculation method for the economic view and a leasing model as a financing option.

The method is to use the parametres of the Case study as variables and coefficients in the efficiency formulae in the energetic analysis as well as in the economic calculations. The life cycle assessment (LCA) data is derived from existing fuel cell LCA studies.

2.1 Definition of the analysed system

2.1.1 Case study: a single-family home located in Tyrol

To calculate the energetics and economics of a house powered by a fuel cell, a single-family home with their annual heat and power requirements will be studied, referred to as "the small system".[1] The location of Innsbruck/Tyrol is chosen *(due to the in-laws of the author)* to provide the appropriate weather data, for which three model days apply: a Sun-rich day supplying direct power, a day with excess energy to produce hydrogen, and employing the fuel cell as the main power source in Winter or on Sun-poor days

2.1.2 System overview

The photovoltaic installation converts primary energy of the Sun and supplies it to an inverter. Electric appliances of the small system are supplied directly, including the heat pump (supplying heat for space heating), and any excess may charge a lithium-ion battery or run the electrolyser to produce hydrogen, which is stored in the H2-Storage. A buffer tank supplies hot water, and is run electrically as well as accumulating waste heat through a heat exchanger. Part of the electrical appliances are also the charging stations for the E-mobility. The H2-Storage may supply the fuel cell or a hydrogen car. Any absolute excess may be fed into the grid, if an appropriate feed-in tariff allows.

[1] The term "the small system" may be seen in contrast to a multi-family home which would be referred to as "the medium system". While the latter is not considered in this master's thesis, facts of the small system may be extrapolated for any future calculations.

Figure 2.1 provides an overview of the described system to be calculated and analysed.

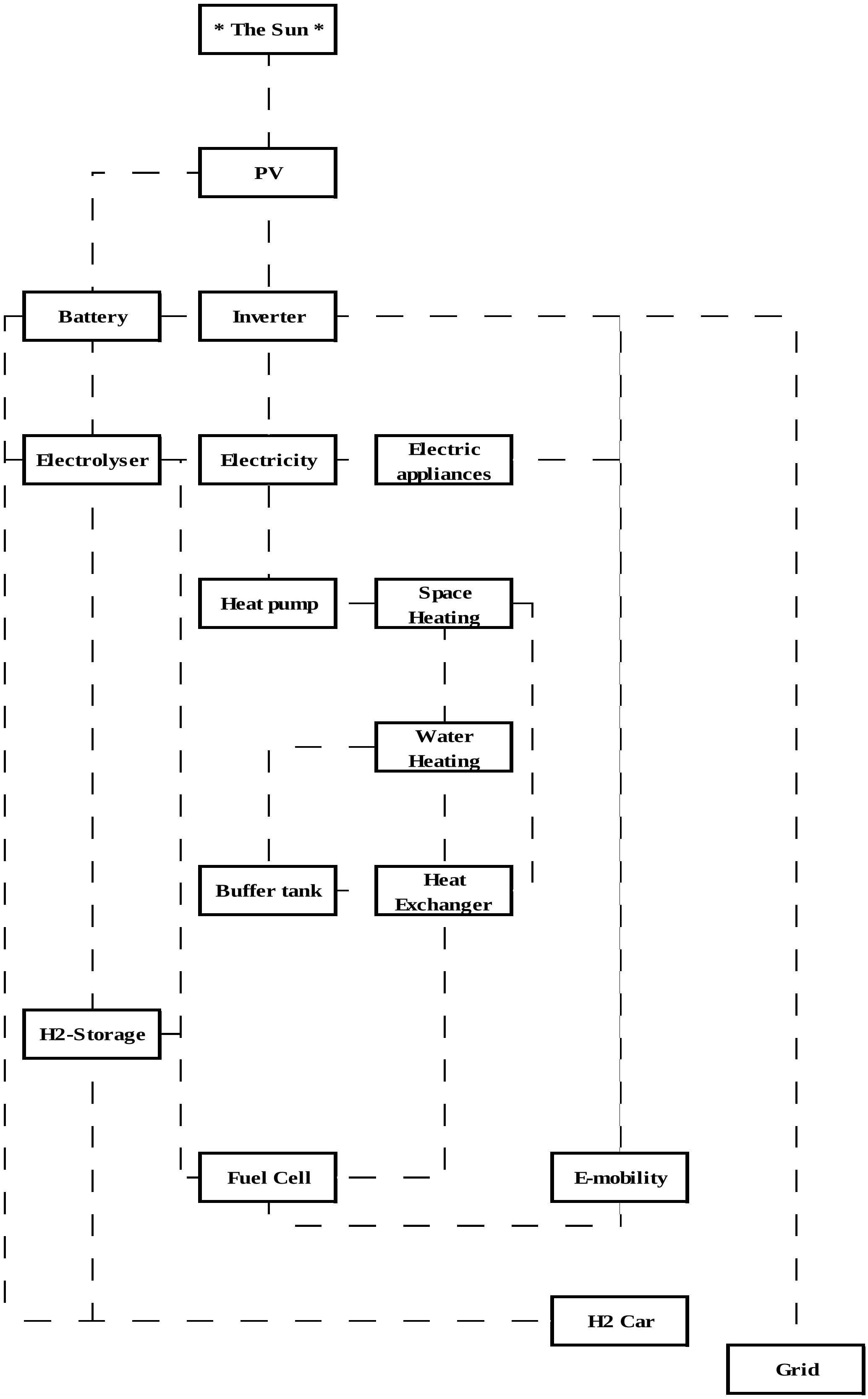

Figure 2.1 Structural overview of the energy supply and storages *Source: own construction*

2.2 Energetic analysis

Two efficiency formulae are introduced that will be calculated in Section 5. First, one formula for the fuel cell itself with several sub-formulae relating to the efficiency of the electrochemical conversion, the thermodynamic efficiency, and the auxiliary equipment. The second formula takes into account the necessary related equipment of the fuel cell.

2.2.1 Fuel cell efficiency calculation methods

A fuel cell can be measured by it’s thermodynamic efficiency (η_{Therm}), i.e. the maximum amount of energy released from the oxidation of hydrogen. It depends on factors such as lower heating value (LHV) and higher heating value (HHV) of water, for which the values are given with 94.5% and 83.0% resp., by Nave (2013) with data from Schroeder (2000). Together with other components such as electric efficiency (η_{Volt}), current efficiency (η_{Curr}), and the auxiliary equipment (η_{Aux}), they are multiplied to result in total efficiency ($\eta_{FuelCell}$). Hydrogen conversion charts are found in Annex 1.

Two sources, Uni Münster and ZSW (2001) describe the total efficiency formula as

$$\eta_{FuelCell} = \eta_{Therm} * \eta_{Volt} * \eta_{Current} * \eta_{Aux} \qquad (1)$$

Kurzweil (2013) and Walkowiak (2005) also employ thermodynamic, electric and current efficiency components, but use two other components instead of the auxiliary equipment efficiency, namely the efficiency of the heating value (heating value of hydrogen that reacted in the fuel cell divided by heating value of hydrogen introduced into the fuel cell) and the efficiency of the fuel itself (quotient of actual fuel used versus fuel input, in terms of volume). The latter version however is not used in this thesis.

2.2.2 System efficiency calculation methods

Based on the Case study mentioned in Section 2.1, the overall system efficiency (η_{System}), relating to solar electricity, shall be assessed by an own construction consisting of efficiencies of the PV installation (η_{PV}) multiplied by that of the inverter ($\eta_{Inverter}$), the electrolyser ($\eta_{E\text{-}lys}$) and the storage of the hydrogen ($\eta_{H2\text{-}Stor}$), and using these as a weighting of the fuel cell efficiency coefficient $\eta_{FuelCell}$ from Section 2.2.1:

$$\eta_{System} = \eta_{PV} * \eta_{Inverter} * \eta_{E\text{-}lys} * \eta_{H2\text{-}Stor} * \eta_{FuelCell} \qquad (2)$$

In Figure 2.2 the Sun's energy is shown as the primary energy (PE). After the photovoltaic conversion η_{PV} into electricity which is being further processed by the inverter $\eta_{Inverter}$, to convert from direct current (DC) to alternative current (DC), efficiency of the inverter plays a role, before it results in the final energy (FE). For the purposes of the Case study the orange box "Market/Price" is not relevant as FE Supply and FE Demand is equal. The electrolyser with it's efficiency $\eta_{E\text{-}lys}$ as well as the hydrogen storage coefficient $\eta_{H2\text{-}Stor}$ are two components that come before the useful energy (UE). Therefore, the system efficiency to be calculated relates to the process from PE over FE to UE, but does not include the actual supply of energy service (ES).

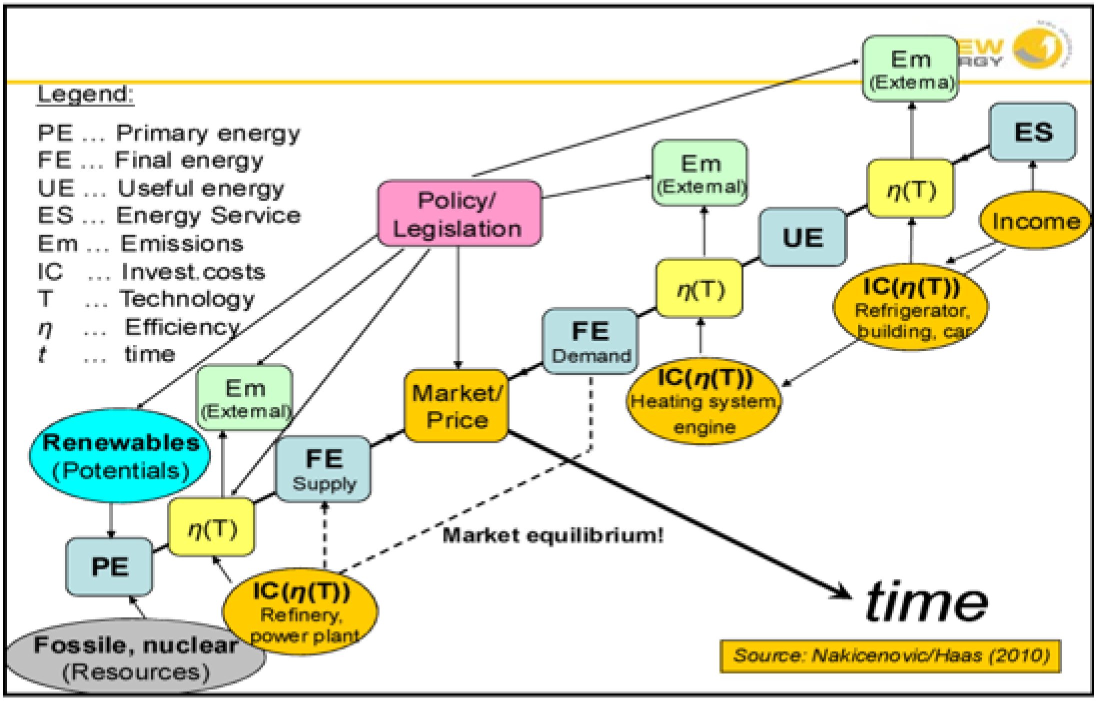

Figure 2.2 From primary energy to energy services *Source: Nakicenovic/Haas (2010)*

2.3 Ecological analysis: Lifecycle Assessment

Since the 1960s ways were developed to assess input of materials and output of emissions of various products and processes which were manifested in standardised procedures, foremost by the International Organisation for Standardization (ISO) as well as by the United Nations Environmental Programme (UNEP); Nogueda (2013).

To assess a fuel cell, beginning with material sourcing of parts, the production and delivery, until actual operation and end-of-life, partial-recycling and partial-disposal, requires extensive analysis beyond the scope of this paper. For the present purpose one Life Cycle Assessment (LCA)-model is chosen as basis, the ISO 14040/14044, developed in 2006 by the International Organization for Standardization, Geneva, being a "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle"; Guinée et al (2001, in Nogueda).

The steps of the LCA consist of the following and are outlined in Figure 2.3 below.

a) Goal and Scope definition; i.e. setting the boundaries and defining the functional unit

b) Inventory analysis; mainly dealing with the data collection of the entire life cycle

c) Impact assessment; looking at environmental factors and discussing the relevance

d) Interpretation; defining points of action and identifying room for improvement.

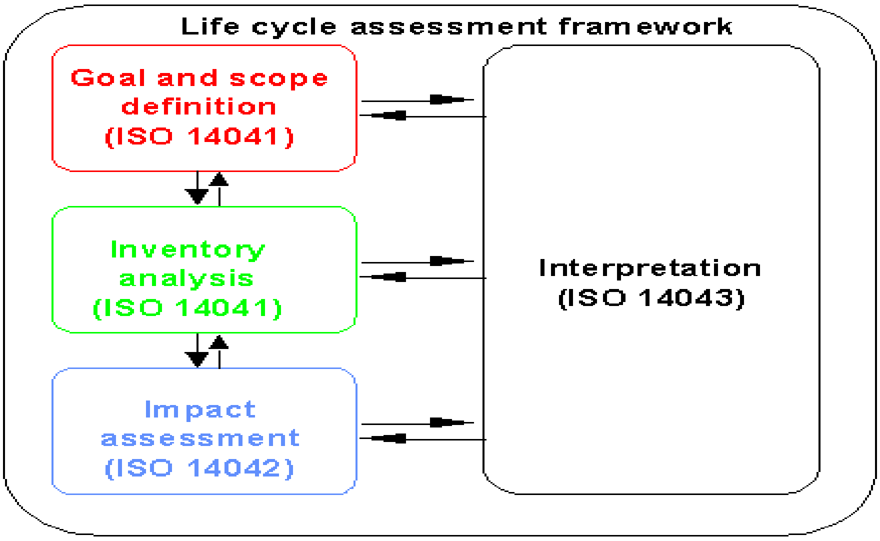

Figure 2.3 ISO 14040/14044 LCA of 2006 *Source: Boustead (2013)*

The assessment in Section 6 is based on works by Pehnt (2001), van Rooijen (2006), Sørensen (2005, 2011), Masoni (2011), Staffell (2010, 2012) and Schwaiger (2012).

2.4 Economic analysis

For the purpose of this master's thesis the economic analysis achieves two goals. First, to assess the scope of investment and running cost, as well as possible grants and subsidies, and secondly a leasing model to be calculated for the small system, in relation to a subsequent discussion on other ways of financing residential fuel cells in Section 7.

2.4.1 Investment and cost calculation method

The investment and cost calculation is derived from inputs of the Case study and specifically relates to the PEM fuel cell as to be described in Section 4.6. The four following blocks will be added up: the first block is the fuel cell module itself. The second block consists of the PV, the inverter, the heat pump, the short-term storage, the hot water storage and a heat exchanger. The third block consists of the electrolyser and the actual storage facility of the hydrogen gas. The fourth and final block relates to the mobility, which given by the system includes an E-scooter and the hydrogen car. The fuel cell price was verified with the manufacturer as is the focus of this master's thesis, while the other items are summarised with one amount per block, as they are variables. Figure 2.4 shows the four blocks building on one another.

Block	Items	Euros
I	Fuel cell: Fronius 25 F	
II	PV, inverter, heat pump, short-term storage, hot water storage, heat exchanger	
III	Electrolyser, hydrogen storage	
IV	E- and H2-mobility	
TOTAL		

Figure 2.4 Total investment consisting of four blocks *Source: own construction*

The direct cost items occurring each year only consists of the annual maintenance fee. Indirect cost such as amortisation of certain equipment, as well as end of life-disposal expenses, are due at the end of the useful life of the fuel cell, e.g. after 20 years.

Grants and subsidies will be mentioned separately but not incorporated into the calculation, as it may vary by geographic location as well, and are subject to approval.

2.4.2 Leasing model

Based on Section 2.4.1, consisting of the initial investment and the annual running cost, the question can be raised how to finance this endeavour. On option is through leasing. Leasing structures are known to be common for financing cars, computers, IT-hardware, soft drink vending machines and warehouse inventory, and recently also wind parks. The user enjoys the benefit but does not own the equipment; this is a matter of choice.

Furthermore, contracting models, as a related form of leasing, have emerged in the area of energy financing. In Austria, they are sofar offered by energy contracting companies, as well as the subsidiaries of utility companies, e.g. Wien Energie, EVN, MEA Solar (E-Wels), ProContracting (Innsbrucker Kommunalbetriebe together with Energiecomfort), and applied to buildings such as schools, farms and industry for residential heat and power. Staffell & Ingram (2010) reported that fuel cell leasing has already been done in Japan, with the positive effect that fuel cells were more likely to be recycled than if they were owned by private household owners.

The following set of equations are based on Hearn (2013) and determine the lease rate.

$$\textbf{Lease payment} = \textbf{Depreciation fee} + \textbf{Leasing fee} \tag{3}$$

$$\textbf{Depreciation fee} = \frac{\textbf{(Net capitalised cost – Residual value)}}{\textbf{Term}} \tag{4}$$

$$\textbf{Leasing fee} = \textbf{(Net capitalised cost + Residual value) * Money factor} \tag{5}$$

$$\textbf{Money factor} = \frac{\textbf{Lease charge}}{\textbf{(Net cap. cost + Residual value) * Term}} \tag{6}$$

Together with the annual running cost, and having determined the lease rate a cash flow, to serve as an overview over the period of the fuel cell operation lifetime, can be constructed, as will be seen in Section 7.3.

Finally, a brief discussion is offered in Section 7.4 when considering alternative financing options of fuel cells in other cases of buildings, which may be of the residential, communal or commercial type.

3. Background: fuel cell and hydrogen

This section reviews the technical background of fuel cells and hydrogen in relation to the residential application. Section 3.1 begins with milestones of electrochemical conversion to highlight the path towards the proton-exchange membrane fuel cell, while additional information can be found in Annex 3.

In Section 3.2 the fuel cell is looked at deeper and wider. On the one hand into the components to provide a basis for ecological considerations, and on the other hand to understand the market situation of residential heat and power, including existing examples, to give an impetus for the economic discussion. Acceptance by society depends on the level of penetration of fuel cells. A review of fuel cell activity in Austria is given in Annex 4.

Section 3.3 reviews the production of hydrogen, storage, transportation and the safety.

3.1 Short history of the fuel cell and hydrogen

a) Precursors of the fuel cell

In December 1838, Sir William Robert Grove (1811-1896) wrote on experimenting ‘with two sets of troughs, one consisting of alternate plates of iron and unglazed porcelain, and the other of alternating plates of copper and porcelain. He let in sulphate of iron with dilute sulphuric acid, muriatic acid [today called hydrochloric acid] and nitric acid resp. In the iron trough only the nitric acid showed a light current. In the copper trough, with sulphate of copper, the sulphuric and nitric acids did not render anything, but the muriatic acid, diluted with twice the water, sent the rotating magnet whirling for several hours, without the addition of fresh acid.’ So the chlorine travelled to the metal, and the hydrogen formed H_2O with the oxygen of the sulphate, the latter reduced to sulphur, and set the rotating magnet into “electro-motive action”.

> “It would seem then that the best form of combination would be one with two metals and two electrolytes, the generating metal being one which has the strongest affinity for the anion of the electrolyte in contact with it, while the other solution is most readily decomposable by its cation and does not cause a precipitate upon which its own anion would readily react; zinc with muriatic acid and copper with sulphate of copper fulfil these conditions to a great degree; if these principles be correct, very superior combinations may be discovered.”
>
> Grove (1838)

In the same year (1838), Christian Friedrich Schönbein (1799-1868) reported similar findings, which he termed ‘polarisation effect’, a current produced in an acidic solution due to “the union of hydrogen and oxygen [on platinum wires]”. The two knew each other. Grove, also a lawyer, represented Schönbein in court cases; Epsom (2013).

In 1842, Sir Grove reported that he used platina foils inside glass tubes [electrodes]. Figure 3.1 shows his illustration as per “Historical Publications in Electrochemistry”. Alternatingly oxygen (ox) and hydrogen (hy) were supplied to the tubes, and hydrogen was used up ‘twice as fast as oxygen’. He determine that ‘three elements [are necessary] for chemical actions’; electrolyte, reactants and catalyst. In Grove’s words:

> “This battery is peculiar in having the current generated by gases, and by synthesis of an equal but opposite kind at both anode and cathode; it is therefore, theoretically, more perfect than any other form, as the batteries at present known, act by one affinity at the anode, and have to overcome another at the cathode.”
>
> Grove (1842)

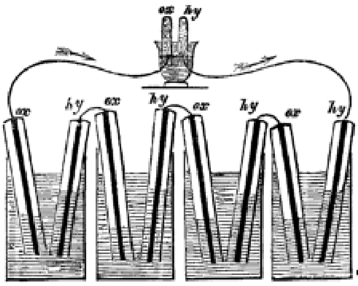

Figure 3.1 Gaseous voltaic battery from the year 1842 *Source: Grove (1842)*

b) Considerable developments at the turn of the last Century

In 1894, Friedrich Wilhelm Ostwald (1853-1932) reported on experimenting with zinc and platinum electrodes. He used sulphuric acid as electrolyte, and applied it to the tube containing the platinum electrode, not the zinc electrode, reasoning that ‘if the zinc is to dissolve, it requires ions for that, which can only be supplied by the hydrogen’ giving off the H^+-protons, travelling through the electrolyte to the zinc; Ostwald (1894)

In 1901 Ernst Wiss (1870-1945), employed by Griesheim, received an assignment by Count Zeppelin to deliver hydrogen for the airship named after him; a challenge no one was prepared to take up. ‘After several accidents with casualties, by 1909 he was able to supply 2,750 m^3 H_2 in 500 cylinders at 170 bar.’ The 1937 Lakehurst incident did not stop research on hydrogen to continue, on either side of the Atlantic; Aichele (2004).

c) Developments by Fronius in Upper Austria

In 1945 Günter Fronius (born 1907) constructed a device to re-charge batteries 'so that people would not have to throw them away', in his own words. See Figure 3.2 below.

Figure 3.2 Mr. Fronius (founder) constructed a device to re-charge batteries *Source: Fronius (2012)*

d) Enhancements in the 1950s and 1960s

Francis Thomas Bacon (1904-1992) experimented with potassium hydroxide (KOH) as the electrolyte, as it was 'less corrosive to the electrodes' and was the first to pressurise the gas. In 1959 he built a 6 kW-fuel cell that provided 'power, heat and clean drinking water'. Thereafter, the development of the fuel cell picked up rapidly.

In the mid 50ies, Willard Thomas Grubb, working at General Electric in Schenectady, was the first to use a polymer membrane as the electrolyte [solid, rather than liquid]. He developed a permeable 'sulphonated polysterene ion-exchange membrane' which replaced the liquid electrolyte; see Figure 3.3. Soon after, his colleague Leonard Niedrach enhanced it by "depositing platinum onto this membrane", which served as a catalyst for the reaction, and it came to be known as the "Grubb-Niedrach fuel cell".

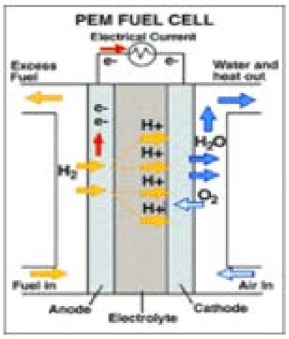

Figure 3.3 Grubb-Niedrach fuel cell *Source: Cleveland (2013)*

In the 60ies the membrane was re-designed by Walther Grot, at DuPont, by using a 'sulfonated tetrafluoroethylene'; and called NAFION™, which is still in use today.

d) The first alkaline fuel cell car and the manifestation of PEM fuel cells in cars

After the experiences in space missions, the fuel cell found it's application in transport. In 1970 Dr. Karl Kordesch (1922-2011) at TU Graz, installed a 6 kW alkaline fuel cell (with a liquid electrolyte, similar to Bacon) into an Austin A 40. It featured lead accumulators (20 kW), carried gas cylinders on the roof and was said to have a range of 300 km. This may have been the first car to employ a fuel cell; Geitmann (2006).

Geoffrey Ballard (1932-2008) and David P. Wilkinson in the 1980ies contributed as well considerably to the PEM fuel cell, with focus on applications in transportation. Further, Wilkinson (2001) stated that the focus shifted from 'efficiency-driven' to 'improving reliability and reducing cost'. He highlights storage to be a main issue.

3.2 The fuel cell

Section 3.2.1 provides information about the chemical, thermodynamic and kinetic aspects of the fuel cell relevant to the equations of the energetic analysis in Section 5. Section 3.2.2 bears environmental implications with regard to the ecological analysis. Sections 3.2.3/4 provide some background for the Case study and economic analysis.

3.2.1 The proton-exchange membrane (PEM) fuel cell

The fuel cell is a gas voltaic battery which derives the gas, referred to as the fuel, from an external supply, rather than containing the charge itself, like a common battery does.

a) Oxidation and reduction reactions

Two electrochemical reactions occur at the electrodes; the oxidation and the reduction. As in Figure 3.2, the fuel cell links to a circuit of energy consumers, the electrons leave by the anode and provide the current to do work. The H^+-protons, that had previously given up their bond with the oxygen from the H_2O during the electrolysis, are now, in the fuel cell, passing through the proton-exchange-membrane again, to meet the O_2 at the cathode, in preparation for the oxidation reaction, which is only made possible by returning electrons from the circuit. The fuel cell process is the reverse of electrolysis.

b) Thermodynamic aspect of a fuel cell

Thermodynamically speaking, energy was put in, in order to be released again. This energy was meanwhile stored in the form of hydrogen. Once the hydrogen is oxidised, the thermodynamic efficiency η_{Therm} is the quotient of the possible free energy of the endothermic reaction taking place in the fuel cell, defined by Gibbs as that portion of energy which can be reversed into it's previous state, divided by the total reaction enthalpy (change) of water, at a given temperature and pressure; Kurzweil (2013).

c) Kinetic aspect of a fuel cell

Kinetically, i.e. in terms of electricity, the charge in the electrons, as was explained in the short history about Grove's and Ostwald's experiments above, accumulated at the anode, and because the membrane does not allow for the electrons to pass. Since the H^+-protons are attracted to the oxygen in the cathode and have to travel through the membrane, the only way for the electrons it is to circumvent the membrane and follow through the circuit. The electron current is highest at the anode and lowest at the cathode and this depends largely to the Ohmic resistance, as well as the time it takes for electrons to complete the bond between H_2 and O_2 resp. O (Uni Münster).

d) Overpotential between the electrodes

The overpotential, as per Uni Münster, in the fuel cell is shown in Figure 3.4. First, before the circuit is opened, the current flow is still 0 and the voltage is highest at close to 1.2V on the y-axis. As soon as the circuit is opened, the current drops rapidly at first (Line 1). This is due to the overpotential. During normal activity, then, (Line 2) the usual resistance of the circuit, measured in Ohm, will cause the voltage to drop in a linear way as the current of electrons carry out useful work. Like in a battery the power is reduced, however while a battery contains it's absolute load, the fuel cell receives fresh supply of hydrogen through the anode and oxygen, or air, at the cathode, until the end of the supply or when the concentrations of the reactants change (Line 3).

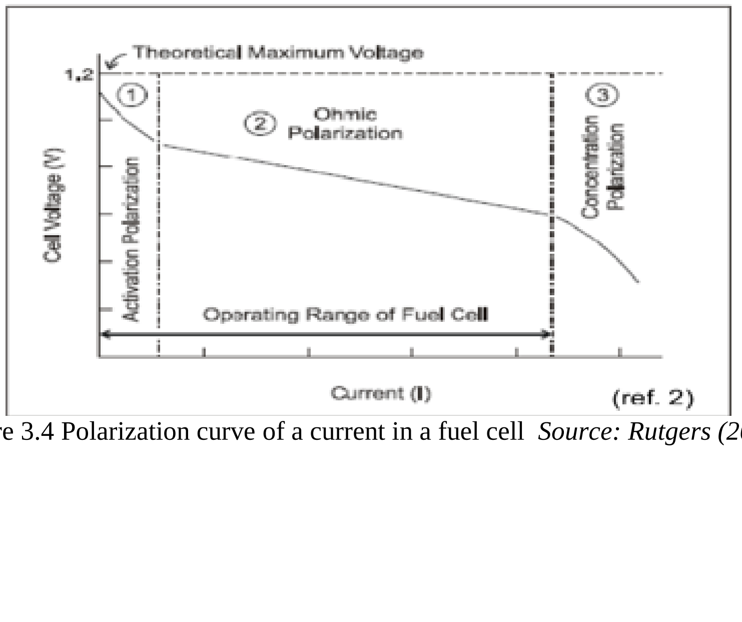

Figure 3.4 Polarization curve of a current in a fuel cell *Source: Rutgers (2013)*

Voltage efficiency η_{Volt} is the proportion of the voltage at the cathode (i.e. at the end of the polarisation curve) to the voltage at the anode (at the beginning of the curve). The current efficiency η_{Curr} is based on the Faraday constant, Walkowiak (2005), relating to the number of electrons that can react on a given surface at a specific time. Detailed chemical, thermodynamic and kinetic calculations are shown in Section 5.1.

3.2.2 Components of the PEM fuel cell

The main components of a fuel cell are the membrane, bipolar plates and the catalyst. Baker & Zhang (2011) cite the main challenges to be ‘insufficient durability of the fuel cell and degradation of the membrane and other components’. The significance is that it infringes on the output of the fuel cell resp. the amount of hydrogen per cycle, as the latter needs to be produced by applying energy; therefore the less hydrogen wasted, the more energy saved.

a) The membrane

The central function of the membrane is to let the ions permeate, but not the electrons. It also has to be non-conducting, non-oxidant and does not accumulate any moisture. It has to fulfil the ‘three-phase boundary’; must not get too hot, nor too wet, nor dry. Nafion, developed by Grot in the 1960s, is still in use today. Fluorine, extracted from ores and in chemically complex ways polymerised to membranes, is a market predicted to grow to 5.94 million tons by 2017; PRWeb (2012). According to Steele & Heinzel (2001) hydrocarbons could not replace fluorine sofar, as they are ‘thermally less stable’.

Research in the last few years has centred on trying to use less platinum, more for economic reasons rather than ecological. Some material is provided in Annex 5.

b) The bipolar plates

The bipolar plates, in the form of a porous graphite structure, referred to as the ‘flowfield’, allow for the gases to diffuse consistently, for water that is used for cooling of the cell to pass, and, to transpose excess heat from the membrane to prevent overheating. According to Walkowiak (2005), they consume half the production cost, and research focuses on optimising the process by introducing more automation methods, such as extrusion, or die casting the graphite, or using stainless steel as an alternative (though it is susceptible to degradation due to the hydrogen over time); HZwei (01/12). A table on different types of elastomeric seals is found in Annex 6.

Figure 3.5 shows the main components which make up the fuel cell. The membrane acts as the electrolyte in the solid form (not liquid), and has the advantage that it also acts as the separator between the two electrodes; i.e. one for the fuel (hydrogen) and the other one for the air (oxygen), as are affixed directly in the form of a coating on the membrane, to maximise the surface area at which gas diffusion shall take place.

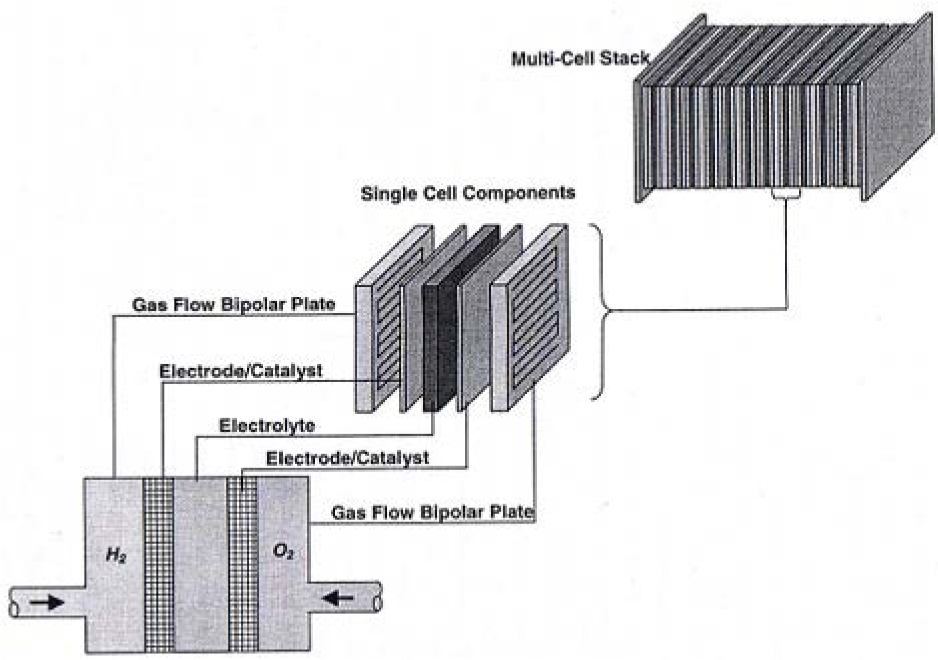

Figure 3.5 Membrane-Electrode Assembly (MEA) of a fuel cell *Source: Baker & Zhang (2011)*

c) The catalyst

A lot of research has gone into structuring the platinum as the catalyst, also in terms of it's nano-structure, or replacing portions by carbon or graphite. 90% of the world's platinum demand is mined in South Africa at 130 tonnes per year; Mining Intelligence Database (2013). According to Baker & Zhang (2011), Ballard managed to reduce the platinum content in the membrane by a factor of 10 from 4.0 to 0.4 mg/cm², replacing parts of it with carbon. The carbon does not replace the platinum as the catalyst, rather it improves the nano structure so that the electrons can flow at less resistance. In addition, research is also being conducted using ruthenium, palladium and cobalt to replace the platinum.

d) Related equipment of the fuel cell

A visual representation of the major auxiliary equipment is shown in Annex 7. They consist of the air supply, the hydrogen supply, a quick coupling, the cooling circuit with pump and valve, the heat exchanger and a distributor, and a flush valve, a bleeder valve and a separator. These items incur losses of approx. 95%, but due to temperature, also contribute by providing heat which can be used, and gains are noted.

e) Lifetime of a fuel cell

According to IEA/OECD (2007), stationery PEM fuel cells can have lifetimes of up to 30,000 hours, and that "depends on operating conditions (start-up temperature, humidification, and fuel purity)". Table 3.1 compares lifetime as well as electrical efficiency of PEM fuel cells with that of SOFC, molten carbonate-fuel cells and direct methanol-fuel cells.

Table 3.1 Comparison of fuel cell-types by lifetime and efficiency *Source: IEA/OECD (2007)*

		PEMFC	SOFC	MCFC	DMFC
Operating Temp. (°C)		80-150	800-1,000	>650	80 100
Fuel		H_2	H_2, hc	ng, hc	methanol
Electrical Effic. (%)		35-40	<45	44-50	15-30
Applications		FCV Power	Station. Power	Station. Power	Portable Power
Lifetime (h)	FCV	2,000	6,000	8,000	na
	Power	30,000	20,000	20,000	
Target lifetime (h)	FCV	4,000	40,000	40,000	
	Power	20,000	60,000	60,000	na

3.2.3 Current applications in residential combined heat and power (CHP)

While mobility is one major focus of fuel cells today, and while a hydrogen car will also be briefly discussed in the Case study in Section 4, the central topic of this paper remains the fuel cell as it is used in buildings with regard to combined heat and power.

a) Residential SOFC and PEM FC

Some of the fuel cells that have been implemented in Europe and Japan, source natural gas from the public gas grid, and, as mentioned, reform methane (CH_4) to a hydrogen-rich gas, which a.o. causes carbon emissions. The typical fuel cell size for this application is between 0.75 and 1.5 kW, although some manufacturers also offer CHP in the 5-10 kW-category, such as RBZ (Riesaer Brennstoffzellentechnik GmbH).

Table 3.2 compares some of the residential fuel cells for which data could be found. Vaillant is the oldest in the market, Baxi is English, CFCL is Australian, and Panasonic with the Ene-farm programme and government subsidy has delivered 20,000 units.

Table 3.2 Comparison of sold residential fuel cells *Source: HZwei (2012, 2013)*

Name	Location	res-CHP model	Type	kW el	kW th	Efficiency	Price (€)	Units sold
Baxi Innotech	Hamburg	Gamma 1.0	PEM FC	1	1.8	91%	20,000	140 by July 2012
CFCL	Heinsberg	BlueGen	SOFC	1.5	0.6	85%	28,000	250 by April 2013
Panasonic	Osaka	*Ene-farm*	SOFC	0.75		95%	16,000	20,000 by July 2013
RBZ	Glaubitz	*inhouse5000*	PEM FC	1,5	3	92%	25,000	n.a.
Vaillant	Remscheid	EURO 2	SOFC	1	2	85%		Callux programme

Solid-oxide fuel cells (SOFC) are mainly distributed in the market for residential CHP. But they operate at temperatures between 800°C and up to 1,000°C; Boetius (2005). Both technologies are still on the market, i.e. natural gas being reformed to hydrogen versus electrolysis from photovoltaic. It remains to be seen which way it develops.

b) Current market price of residential fuel cells

Prices for PEM FC and SOFC are mentioned in Table 3.2. According to a survey by Staffell and Green (2012), fuel cells in the category 0.7 to 1.5 kW, range between USD 24,000 (*EUR 17,700*) and USD 28,000 (*EUR 20,650*). See Annex 8 for further details.

A 1.5 kW BlueGen-SOFC is produced by CFCL (Ceramic Fuel Cells Limited, an Australian company founded by an Austrian in the 90s) and is quoted at € 28,000 (incl. installation costs), with € 600 annual maintenance costs (resp. EUR 2,100, if the gas from the grid is included). Previously, EUR 1,400 were quoted. It is assembled in Heinsberg in Germany. 250 units have been sold until April 2013; HZWei (2013).

Panasonic of Japan are researching, producing and marketing PEM FC and SOFC, which are also reforming natural gas. As a standard, a hot-water storage tank and a back-up boiler are integrated from the start into the systems, and the 0.75 kW-model sold at JPY 1,995,000 (*€ 14,950*), which is said to be JPY 760,000 (*€ 5,700*) cheaper, than the previous model. In a joint venture with regional gas companies, foremost Tokyo Gas Co., Ltd., 21,000 units have been installed in Japan until December 2012. They are subsidised under a programme called Ene-farm, in place from 2010 to 2015.

c) Production cost breakdown of residential fuel cells

To illustrate, Figure 3.6 summarises the different costs could make up the Enefarm-cell, if, according to Staffell & Green (2012), '3 million systems were produced and respective learning curves realised'. As the Enefarm is an SOFC-model, the 61%-share of the balance of plant relates mainly to the reformer; which does not apply in the PEM FC-case. Staffell & Green (2013) find that for PEM FC the expensive material is the platinum, and suggest that rather than 'producing the hydrogen on-site', it may be an option to centralise hydrogen production (i.e. short of development cost).

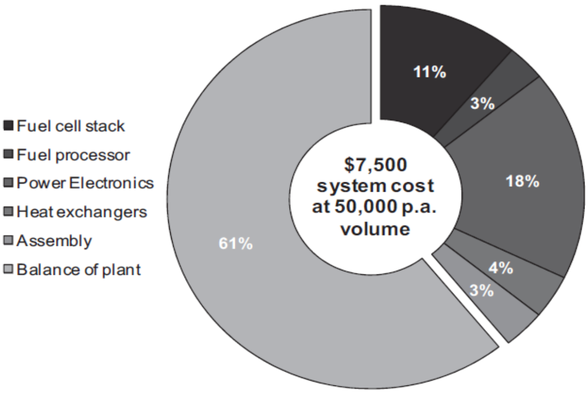

Figure 3.6 Breakdown of manufacturing cost of Enefarm-FC *Source: Staffell & Green (2013)*

d) Residential CHP market forecast

According to Pike Research of the United Kingdom (UK), stationery fuel cells (as opposed to mobile fuel cells, and which, next to residential fuel cells include structures such as for telecommunication masts) are forecasted to exceed USD 2.6 billion (10^9) by 2017, as in Figure 3.7, of which units sold in Japan in the excess of USD 2.1 billion.

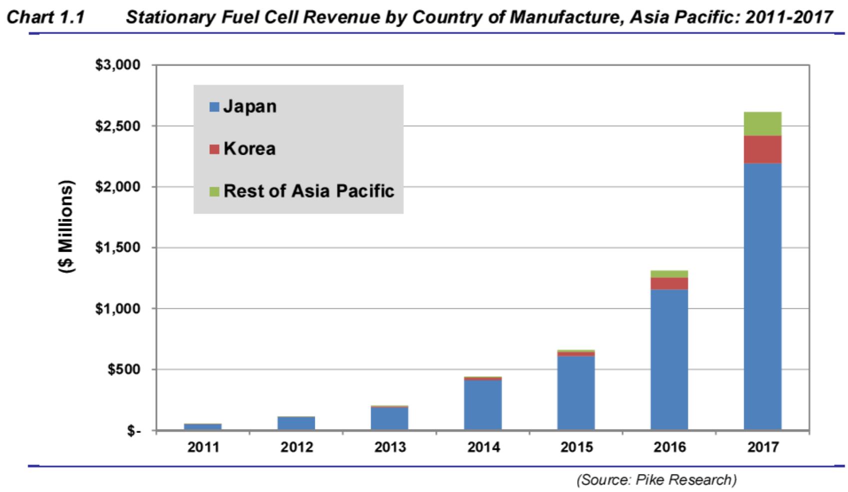

Figure 3.7 Forecast stationery fuel cell sales in the Asia Pacific region *Source: Pike Research (2011)*

By contrast, Figure 3.8 is significant in the sense that Pike Research forecasts individual homes to adopt residential CHP until 2022 at a much steeper rate in annual comparison than multi-family homes. Between 2012 and 2022 cumulative units of both categories, individual and multi-family, shall amount to 13.5 million; as long as the business-as-usual (BAU) scenario goes on, though numbers can fluctuate at any given time, pending market penetration and power outages a.o., as mentioned by Pike (2012).

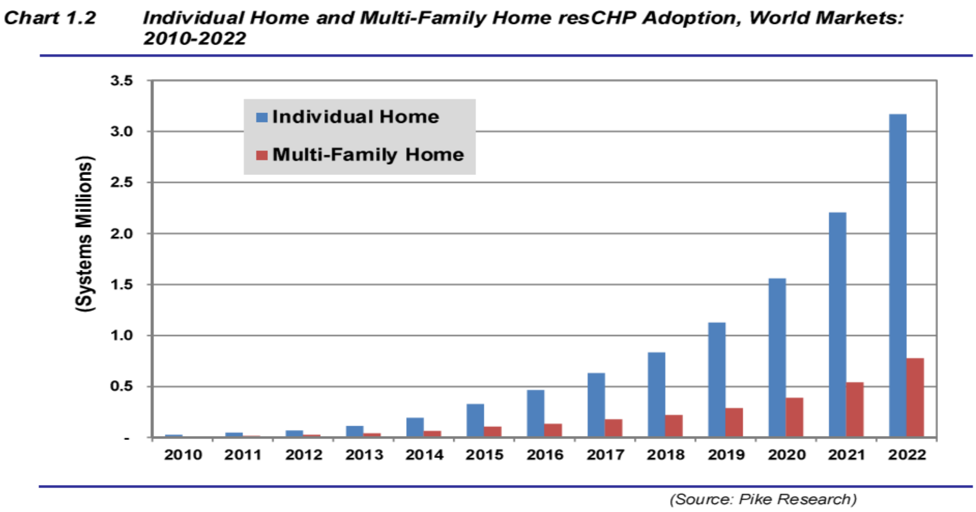

Figure 3.8 Forecast residential CHP in individual and multi-family homes *Source: Pike (2012)*

3.2.4 Existing examples of buildings with fuel cells

Two examples from Austria and one from Sweden, followed by an overview of fuel cell programmes, shall provide a background for the Case study in Tyrol in Section 4.

a) Existing residential CHP examples in Austria

In 2004, a 51 kW-fuel cell by Vaillant was installed in a pension home in Salzburg. It supplies heating to an area of 1,170 m² and warm water to 17 units, sourcing grid gas. The storage tank holds 5,000 litres. A condensing gas boiler serves as back-up. The heating coefficient is 36 kWh/m²/a, compared to that of the Case study; HLK (2004).

In Steyr, a hotel with 90 beds (8,000 guest nights per year) receives power by a Vaillant-cell as well, but of smaller capacity, as electrical power supplied is 4.6 kW, and thermal power 11 kW. The project, valued at EUR 500,000, includes two storage tanks of 500 litres each, one used for pre-heating and the other one for process water; IEWT (2005).

b) Existing residential CHP example in Sweden

In Sweden, an environment information centre, known as “GlashusEtt“, was erected in 2002. It draws Sun energy from 25 m² PV with 3 kW peak, which supply 2.5 MWh per year to the building. The yield is used to power the electrolysis of water. The hydrogen is used as fuel for PEM fuel cell, which supplies 4 kW el and 6 kW th. It also runs on reformed biogas. The funding came from the EC FP5-programme; EC-FP5 (2013). Figure 3.9 illustrates the external views of the buildings containing the fuel cells.

Figure 3.9 Salzburg pension home, Steyr country hotel and GlashusEtt in Hammarby Sjöstad *Source: Ecowatt (2007)*

c) Current residential fuel cell programmes

An early programme, in 2000, on pan-European level was the “European Virtual Fuel Cell Power Plant”. It carried out tests in 31 buildings (with fuel cells of 4.6 kW_{el} and 9 kW_{th}), at a project cost of EUR 8.4 mio, the EU contributed 36% (EUR 3 mio); EUVPP.

In the current programme “Ene-field”, 12 EU Member States from Western, Central and Eastern Europe are participating. It encompasses 960 units of PEM FC and SOFC that are tested until 2017, with a total budget of EUR 53 mio; ene-field (2013). While in the Japanese Ene-farm programme the manufacturers partner with local gas companies, in the Ene-field programme it is the utility companies, alongside research institutes, housing developers and communities. A table of the initiatives is found in Annex 9.

d) Existing residential CHP example in Korea

Sofar the only place in the world where an entire township was developed based on hydrogen and fuel cells is found in Korea, called Ulsan. Hydrogen is sourced from industrial activities as a by-product and supplied to 140 houses using 1 kW-fuel cells, as well as to 10 public and commercial buildings using 5 kW and 10 kW units. The main suppliers in this programme are FC Power, GS Fuel Cell, Hysco and Hyosung.

3.3 Hydrogen

For the purpose of the PEM fuel cell in a residential application, the aim is to derive the hydrogen gas, to be used as the fuel, with the energy input from renewable sources, such as in the Swedish example through photovoltaic. While there are different hydrogen production methods practiced concurrently, the focus in Section 3.3.1 remains on the electrolysis of water. Storage in the form of gas cylinders is described in Section 3.3.2. Though transportation is not so relevant for stationery fuel cells with on-site electrolysis, in the wider sense this topic does include infrastructure and will be addressed in Section 3.3.3 in relation to the hydrogen car featue4red in the Case study. Finally, safety with regard to the handling of hydrogen, as a gas, is a major issue.

3.3.1 Conventional hydrogen production

a) Energy supply chain

In terms of the energy supply chain Ajanovic (2012) hydrogen is considered a ‘secondary energy’ (SE), preceded by solar as the ‘primary energy’ (PE). In comparison to Figure 2.2 above, hydrogen should be seen as an energy carrier. Other forms of secondary energy, as per Ajanovic (2012) include gasoline, electricity, pellets and district heat. That means that from primary energy (PE) source until being delivered to the consumer as final energy (FE), so that it can be used as useful energy (UE), such as heat, light and mechanical work, losses due to conversion and further processing are incurred when producing hydrogen out of Sun energy or other.

The three main reasons why hydrogen should be applied as an energy carrier, according to Baker and Zhang (2011), are: firstly the weight-based energy density of hydrogen is more than that of methanol, ethanol and formic acid (at 33.3 Wh/g). Secondly, hydrogen oxidises at ambient temperature, so it does not need to involve any heating in the initial phase. Thirdly, there are no emissions during the process; as long as there are no hydrocarbons used.

b) Annual World production of hydrogen

The World produces annually 600 billion m³ of hydrogen; DWV (2009). The majority is derived from steam reforming of natural gas, 190 billion m³ in 2004, and partial oxidation of industrial oils, 120 billion m³ in 2004. According to IEA/OECD (2007) 48% of World hydrogen production is sourced from natural gas, 30% from refinery/chemical off-gases and 18% from coal, as can be seen in Figure 3.10. And "the rest from electrolysis", i.e. 4%, as depicted by Baufumé below.

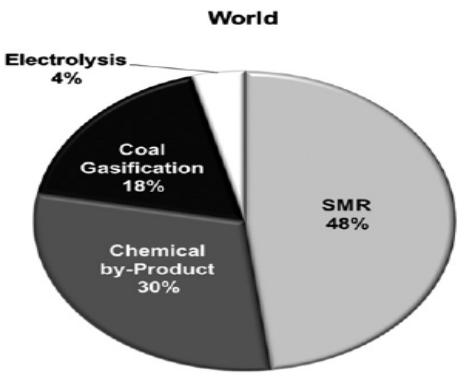

Figure 3.10 Hydrogen production methods *Source: Baufumé et al (2013), from IEA/OECD (2007)*

c) Conventional hydrogen production methods

Most hydrogen production is used and produced by industry and therefore large-scale.

For steam reforming commonly natural gas is used, also methanol and biogas are possible, but several high and low temperature conversion steps require extensive heat, in some cases up to 900°C, which in itself is an energy-intensive process.

Another method is the partial oxidation-process, which is different from steam reforming in that no steam is involved, only the oxidation of the carbon in the hydrocarbons is taking place, and hydrogen is the product; Geitmann (2012). These two processes can also be combined and are termed 'autothermal reforming', as specific quantities of air are added to the reformer, as much as is needed to build up it's own required heat, so it does not need any external supply of heat.

Other conventional methods include generally the gasification of hydrocarbons, such as of coal as well, at temperatures up to 2,000°C and at pressures up to 40 bar, 50 billion m³ in 2004, e.g. DWV, and, in petrochemical production processes, hydrogen as a by-product; Geitmann (2012).

Another thermal procedure is pyrolysis from biomass; Ajanovic (2012). It may also be combined further with a methanisation process to implement the hydrogen from biomass and produce methane for heating; as can also be seen at a plant Güssing in Burgenland.

A cleaning stage has to be introduced after the production as there are rest particles of carbon monoxide that may contaminate the fuel cell in later applications. This is done through desulphurisation, liquefaction, pressure swing adsorption (PSA) and other possibilities. One speaks of hydrogen "grade 6.0" when the H_2-content is 99.9999% (four digits behind the decimal), though this may include H_2O and hydrocarbon particles; as traces of O_2, N_2, CO and CO_2 are unavoidable. Grade 4.5 would be 99.995%; Geitmann (2012).

The abovementioned methods are so-to-say widespread because of the industrial scope at which hydrocarbons are available, on the one hand, and the maturity of the oil and gas industry, and therefore at large scale, on the other hand.

d) Commercial hydrogen cost

According to Geitmann (2012), a 50 l-cylinder (at 200 bar, 9 m³) costs between EUR 35 and 70, plus rent for the cylinder of EUR 0.3 per day. This amounts to EUR 1.30 per kWh.

3.3.2 Electrolysis

a) Water as the feedstock

Electrolysis of water, as per 2004 statistics of DWV, compares to it's industrial peers in the single-digit percentage category, although various manufacturers have introduced electrolysers on an industrial scale (up to 300 kw) such as Norsk Hydro; Ajanovic (2012). Figure 3.8 above records hydrogen production through electrolysis with a 4%-share from a 2007 publication by IEA/OECD. According to HZwei (2011) electrolysers have been implemented since eight decades mostly in combination with hydro power in countries such as Brazil, India, Canada and Norway).

In the residential application, the hydrogen is obtained from natural gas through a reforming stage. It may be inferred that the development of water electrolysis in residential CHP remains slow if the demand for this technology does not increase, and reformers continue to be preferred.

While in the industrial methods mainly natural gas and coal are employed, and while on the basis of biomass gasification and pyrolysis methods are performed, water is featuring in several applications. Thermochemically, i.e. with the application of heat, water can be split, as is also done from solar thermal sources (up to 800°C), for example in the Hydrosol-projects in the Almerían desert in Andalucía; HZwei (2008). Electrochemically, i.e. electric energy has to be put in, will be seen in paragraph f) below. And photoelectrochemically, water is split from direct sunlight; Ajanovic (2012).

Water is being used. So it has to be available. This can be problematic in some countries or regions that do not have immediate or clean supply of water resp. where additional cleaning processes or filtration of salt water are encountered.

b) Three methods of electrochemical water electrolysis

For the electrolysis of water one method is the PEM-membrane as already seen in the fuel cell. It acts as a solid electrolyte and bears similar production stages and cost as the fuel cell. Ultimately, the process is reversed, i.e. water is not produced but split.

There are two more ways to split water electrochemically. One is by means of using an alkaline electrolyte, such as potassium hydroxide (KOH), which has it’s historical roots, where the charge is carried not by H^+-protons but by OH^--ions instead. According to Smolinka this method is capable of producing up to 760 Nm³ in one hour (requiring 3.4 MW per module), which is more commonly used in conjunction with hydropower. The third method is high pressure-electrolysis, an application employing high temperatures of up to 1,000°C, making maximum use of thermodynamics, and resulting in 5.7 Nm³/h (at 18 kW). This also requires warm up-phases and cannot begin instantly like the PEM-electrolyser does. The charge carriers are the O^{2-}ions; Smolinka (2011).

Table 3.3 shows the various forms of electrolysis and compares their working temperature and hydrogen production rate on a per kilogram-basis.

Table 3.3 “Efficiency of H_2 production from electrolysis” *Source: IEA/OECD (2007)*

Technology	Alkaline large-scale	Alkaline high-pressure	Advanced Alkaline	PEM	SOFC
Status	Commercial	Commercial	Precommercial	Precommercial	Prototype
T (ºC) P (bar)	70-90 atm. to 25	70-90 up to 690	80-140 up to 120	80-150 up to 400	900-1000 up to 30
kWh/kgH_2	48-60	56-60	42-48	40-60	28-39

c) Residential PEM-electrolysers

Table 3.4 compares electrolysers of different magnitude from three manufacturers.

Table 3.4 Different residential electrolysers *Source: HZwei (2012/2013)*

Name	Location	Model	Power	Production	Pressure
ITM Power	Sheffield	HPac 10	3.5 kW	0.6 Nm³/h	15 bar
ITM Power	Sheffield	HPac 40	11 kW	5.0 kg/h	15 bar
h-tec Wasserstoff-	Lübeck	EL 30/23	3.0 kW	0.58 m³/h	30 bar
h-tec Wasserstoff-	Lübeck	EL 30/144	18 kW	3.6 m³/h	30 bar
Hydrogen Solutions	Rödermark	1000 S	1.1 kW	0.3 Nm³/h	

Some manufacturers use high pressure-technology, as it saves the compression step. Fronius' new fuel cell model, which incorporates the electrolyser will be considered.

According to Mag. Rührlinger, the Fronius electrolyser produces out of 1 litre water, in one hour, 1.2 Nm³ of H_2, which has a corresponding heating value of 3.6 kWh. It has a maximum power rate of 8 kW, and it works with the high pressure-technology, meaning that the product gas is compressed to 200 bar directly as it is produced. And it can therefore be stored straight away and does not need to be compressed further. In case of carrying H_2 in cars, it is compressed to 700 bar, which requires more energy.

d) Biochemical production of hydrogen

Biochemical processes are significant in terms of future potential, and research is expanding. Rather than using heat, which requires energy, enzymes are responsible for the catalytic reaction. An enzyme is responsible for splitting water into oxygen, protons and electrons, and another at another stage the hydrogenase is re-connecting the protons and electrons to form H_2. The released electrons from the first stage help in an organic way for the algae to grow (resembling the circuit*)*. One enzyme molecule can produce 5,000 molecules of H_2 per second. According to Geitmann (2012) 250 ml of H_2 per day would be sufficient to power a one-family household.

3.3.3 Hydrogen storage and transportation

a) The hydrogen storage challenge

Generally, the ideal way to store hydrogen is still being developed. The most common method to date is in form of pressurised tanks, which are mostly cylinder-shaped or round, depending on the method of transportation. Steel alloy or aluminium wrapped in carbon fibre laminate is used. Lin (1999) states that compressing hydrogen into the cylinder can mean a loss of 5-10% of the quantity. He also offers an equation of state, taken from Redlich and Kwong, which can be found in Annex 10, basically stating that in relation to the ideal gas, hydrogen gas is by 16% worse off; on a molar basis. Lin further recommends that cylinders should not be over-pressurised, and that a maximum lifetime has to be observed, which for example in Canada is 15,000 cycles.
Other ways are liquefying, storing in cryogen tanks, and metal hydride solid structures that bind the H_2 as a sponge; absorption, desorption; Geitmann (2012).

The density of hydrogen by weight is good, by volume it is low and that requires space, which has to be available if to be applied in the residential sector. Table 3.5 compares hydrogen's density of weight and volume to natural gas, methanol, petrol and diesel.

Table 3.5 Overview of hydrogen density by weight and volume and in comparison *Source: Ohl (1997)*

Energieträger	Speicherform	Massenbezogene Energie-dichte [kWh/kg]	Volumenbezogene Ener-giedichte [kWh/l]
Wasserstoff	gas (300 bar)	33,3	0,75
	flüssig (-273 °C)	33,3	2,36
	Metallhydrid	0,58	3,18
Erdgas	gas (300 bar)	13,9	3,38
	flüssig (-162 °C)	13,9	5,80
Methanol	flüssig	5,6	4,42
Benzin	flüssig	12,7	8,76
Diesel	flüssig	11,6	9,70

b) Residential hydrogen storage

This topic is fairly new and there are not many examples yet; a.o. one in New Jersey.

Figure 3.11 shows one aspect of Fronius' "House of the future", where (1) is the PV, (4) the inverter, (2) the electrolyser, but also the fuel cell, because the Energy Cell by Fronius incorporates both in one, so as to save space and material, and (3) the storage.

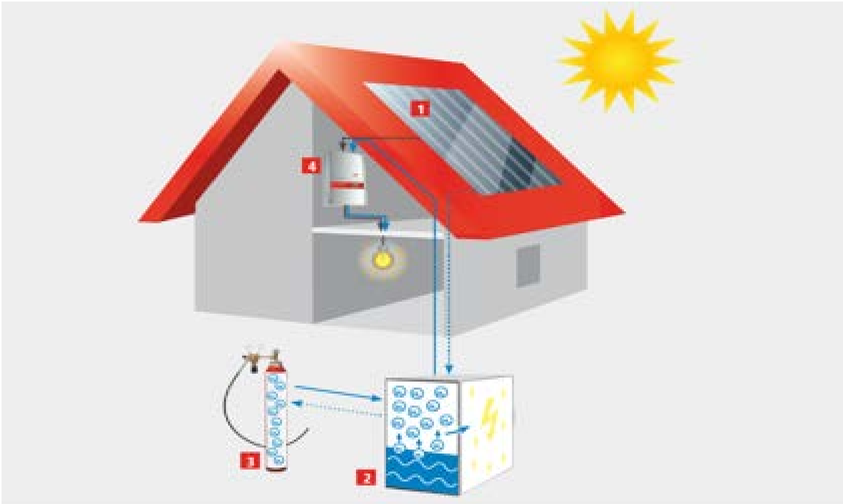

Figure 3.11 Electrolyser and H_2-storage *Source: Fronius(2013)*

12 bundles of four cylinders total 48 cylinders. At 50 litres each and at 200 bar a volume of 480,000 litres, or 480 m³, potentially holds 1,440 kWh equal to 43.2 kg H_2. At an electrolysis rate of 1.2 Nm³/h, it takes 400 hours to fill the storage completely.
It must be noted that gas cylinders filled with hydrogen gas always have red markings.

c) Mass transportation of hydrogen

Industrially-produced hydrogen, usually large quantities, such as from hydro power, is distributed in pipelines or, when supplying H_2-filling stations, transferred by trucks. If it is produced from hydro power, as per Ajanovic (2012), then the cost ranges from EUR 0.16 to 0.29 per kWh, with the largest portion, ca. EUR 0.10 being the production of the hydrogen. Transportation by truck adds to the cost of hydrogen, and if the hydrogen is not pressurised to 300 bar resp. 700 bar, then more volume will be required. It follows that the frequency of truck loads augments proportionally.

d) Hydrogen supply for fuel cell cars

Related to the Case study is the issue of filling the fuel cell car. Sofar there is hardly any hydrogen filling station available for private use in a residential area, and it may take some time. Lessons may be learned from the HyCentA-project in Graz, the OMV-station in Floridsdorf and the upcoming station with PV in Bolzano. See Annex 10.

In HZwei (2008), Dr. Maus wrote about the rate of filling H_2, highlighting a.o. the 3 minute average, like natural gas. As gas comes under pressure, and this is true for the storage above as well, temperature rises. The car could be cooled down (from overnight) or heated up (strong Sun) when entering the station; HZwei (2008).

Figure 3.12 shows the light green patch as the legalised operation boundary (Betriebsbereich), i.e. -40 to 85°C, below that is the subnormal temperature (Untertemperatur) and above 85°C is the overheat (Übertemperatur). At 15°C and 70 MPa the optimum is reached, above which would be the exceedance (Überfüllung), and beyond the cap of 87.5 MPa it is considered over pressure (Überdruck).

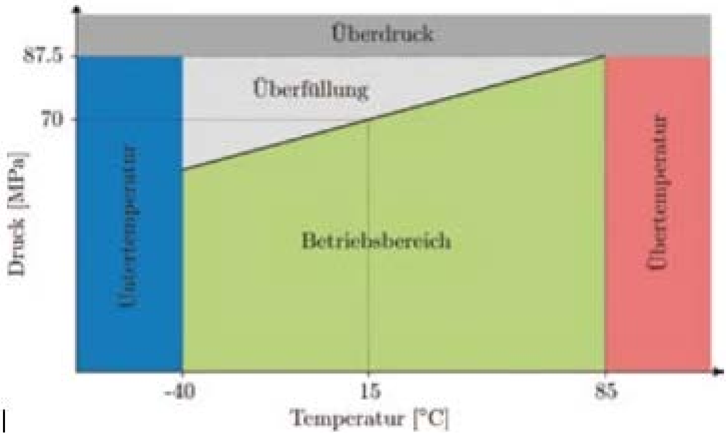

Figure 3.12 Limitations of operating hydrogen-refuelling at 700 bar *Source: HZwei (2008)*

3.3.4 Safety issues with hydrogen gas

a) Hydrogen diffusion flame

While electrolysis, hydrogen storage or the fuel cell are operating, H_2-molecules can dissipate and react with oxygen in the air, causing a bang, as winds or humidity occur. In addition, the atmosphere in turn influences air pressure, temperature, concentration of gases and brings along fine particles. Care has to be taken with an understanding. Therefore, hydrogen safety regulations for this purpose are included in the Appendix.

The flame, as can be seen in Figure 3.13, is blue. It appears briefly and makes a noise; Darling (2013).

Figure 3.13 Hydrogen diffusion flame *Source: Darling (2013)*

b) Hydrogen safety procedure

The Fuel Cell & Hydrogen Energy Association (www.fchea.org) has extensive reviews on hydrogen safety, and another website http://h2incidents.org regularly reports on incidents, for the hydrogen community of the future to inform themselves.

Figure 3.14 raises awareness and helps familiarise with the main risks and measures; Darling (2013); Aachen (2013). Similar to any fire alarm procedure, inhabitants have to know which service number to call in case of emergency. For a multi-family home, a specific person could be designated and trained, similar to responsibilities such as first aid and fire evacuation.

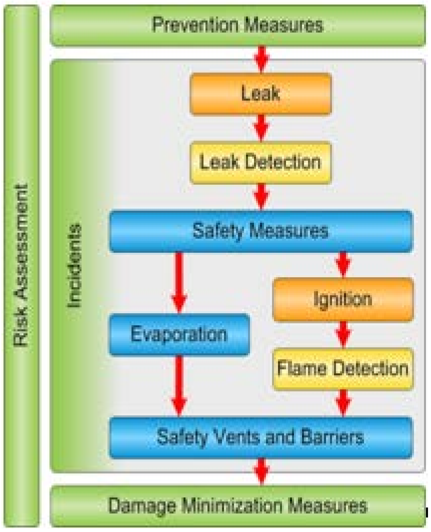

Figure 3.14 Hydrogen safety procedure *Source: Aachen (2013)*

c) Hazards of hydrogen gas

Three hazards are associated with the use of hydrogen; Najjar (2013):

1. physiological: frostbite and suffocation
2. physical: embrittlement and component failures
3. chemical: burning or explosion.

More information can be found in safety data sheets published by gas companies, such as Air Products (http://avogadro.chem.iastate.edu/MSDS/hydrogen.pdf) **or in German by Linde** (http://www.linde-gas.at/sdb_konform/SDS_TG_8360_AT_DE.PDF)**.**

d) Combustion of hydrogen

Further information by Najjar (2013) is provided about the combustion properties of hydrogen in comparison to other fuels. Table 3.6 indicates that hydrogen has the highest energy density by weight, as well as the highest stoichiometric air to fuel-ratio, but that the self-ignition temperature is the least likely to occur.

Table 3.6 Comparison of combustion properties of hydrogen *Source: Najjar (2013)*

Fuel	LHV (MJ/kg)	HHV (MJ/kg)	Stoichiometric air/fuel ratio (kg)	Combustible range (%)	Flame temperature °C	Min. ignition energy (MJ)	Autoignition temperature °C
Methane	50.0	55.5	17.2	5–15	1914	0.30	54–630
Propane	45.6	50.3	15.6	2.1–9.5	1925	0.30	450
Octane	47.9	15.1	0.31	0.95–6.0	1980	0.26	415
Methanol	18.0	22.7	6.5	6.7–36.0	1870	0.14	460
Hydrogen	119.9	141.6	34.3	6.7–36.0	2207	0.017	585
Gasoline	44.5	47.3	14.6	1.3–7.1	2307	0.29	260–460
Diesel	42.5	44.8	14.5	0.6–5.5	2327		180–320

4. Case study: Tyrol

This section combines the theoretical side of the fuel cell and hydrogen-related topics with the practical side. Section 4.2 defines the energy demand of a single-family house (the "small system") of 150 m² living area and four inhabitants, based on the location of Innsbruck in Tyrol. Taking into account weather data for the vicinity, including solar radiation, in Section 4.3, the photovoltaic (PV) installation shall serve as the primary energy (PE) for the small system, with the Sun as it's source in Section 4.4.
Storage of excess energy is covered in Section 4.5, and the application of the fuel cell using the stored hydrogen as the fuel is discussed in Section 4.6. Theory and practice can then be analysed in Sections 5 to 7 energetically, ecologically and economically

The material used in this Section is based on data from the MSc course on renewable energy. By way of applying a practical example to this thesis, based on the homework mentioned, the aspect of **energy storage** is added to the concept of renewable energy.

4.1 Description of the case study

For the entire year (and for the lifetime of the equipment employed), the main source of energy for services related to heat, electricity and transportation shall be derived from PV. The dimensioning of the PV is based on the annual yield and therefore has to include short- and long-term storage as well as all conversion losses and efficiencies of the devices used.
By using a calculation tool to calculate annual PV yield, and by defining Model Days (1. Sun is shining, 2. Excess energy is stored, and 3. The fuel cell supplies the energy), supply, storage and demand can be quantified, and the overall feasibility determined.
A fuel cell manufactured by an Upper Austrian family-owned company, Fronius, is considered in the Case study, as they have experience in stationery and mobile cells.

4.2 Energy services demand of a single-family house

The small system is a single-family home with four inhabitants and has a living area of 150 m². Plus, for the transportation there is one e-scooter and one hydrogen car. For energy services the nomenclature from Nakicenovic/Haas (2010) was used.

4.2.1 Heating

The total annual heating and cooling totals **10,528 kWh th** and will be supplied by a heat pump. Following is the breakdown of the figures that make up this total.

a) Space heating

The living area is 150 m², but the walls have to be included as they absorb heat, and 20% are added to result in 180 m² for calculating the area to be heated. A heating coefficient of 36 kWh/m²/a applied results in an annual demand of **6,480 kWh** thermal.

A heating coefficient of 36 kWh/m²/a corresponds to a building standard in Austria after 2008. It lies between A (≤ 15) and B (≤ 25) on the energy pass scale of OIB, the Austrian Institute of Construction Engineering harmonising building standards. While a 2011 version exists, some Austrian states still apply the 2007 version, including Tyrol. An overall energy efficiency factor (fGEE) of "1" is a grade B on the energy scale, linked to the OIB 2007-standard; so 0.5 would be 50% of that); Gappmaier (2012).

The Energy Performance of Buildings Directive (EPBD) requires heating coefficients to be below 15 kWh/m²/a until the year 2020. Many buildings have to be renovated. In the European Union, 2020-goals aim to improve on the efficiency of building energy by insulating and refurbishing them, and implementing renewable sources. Legislation thereto is provided by the Directive on Building Energy Efficiency (2010) and the EPBD (Directive 2010/31/EU), which succeeded the DIR 2002/91/EC; BMWFJ (2012).

b) Water heating

150 litres of water are the daily requirement of the household, consisting of 30 litres per person times 4, plus an extra 30 litres. For the storage tank the volume is doubled, i.e. 300 litres. As will be seen in Section 4.3, the mean ground water temperature in the vicinity of Innsbruck is 12°C. Heating it up to 60°C once incurs a delta of 48K. 210 full load cycles are assumed per year, thus annual requirement is **3,508 kWh th**.

c) Cooling

Though cooling is not common to be needed in Innsbruck, it is included for future calculations when the temperature may rise. The process is reversed and the energy input is the same. Therefore, one-twelfth of annual space heating equals **540 kWh th**.

4.2.2 Electricity

The entire small system requires electricity; the heat pump as well as all electric appliances, and the mobility, as the electrolyser needs electricity to produce hydrogen. The total amount of power required on an annual basis amounts to **11,781 kWh** el. This figure includes the heat pump, the household electricity and the mobility requirement.

a) Power requirement of the heat pump

The chosen heat pump is manufactured by IDM Energiesysteme GmbH in Lienz, and, by applying a coefficient of performance (COP) of 3.75x to the above thermal power requirement, the required electricity for the heat pump thus results in **2,807 kWh** el. Figure 4.1 shows the location of the heat pump inside the house and the air inlet outside the house. The TERRA IL 7 Complete-model is used. Instead of the indicated COP of 4.05x, 3.75x is used to be conservative. The electrical power input is 1.64 kW el.

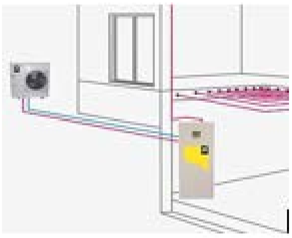

Figure 4.1 Heat pump *Source: IDM Energiesysteme (2013)*

b) Electricity for electric appliances

According to TIWAG, the main utility company in Tyrol, a four-person household in Tyrol uses **4,500 kWh el** per year. Figure 4.2 describes two curves over a 24 hour-period. The blue line is the daily PV yield and the red line the consumption of the household, showing several peaks exceeding the Sun's flow. As excess energy will be stored to cover shortfalls, Section 5.5 will describe Model Days.

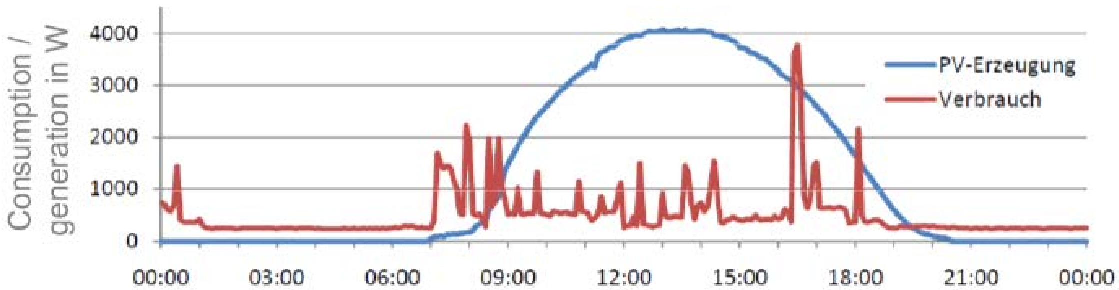

Figure 4.2 Household with PV, comparing consumption and yield *Source: Obersteiner (2011)*

c) Power for e-mobility and H_2-mobility

The annual mobility requirement for E-scooter and hydrogen car equals **4,474 kWh el**.

4.2.3 Transportation

A trend can be seen to use the PV production on the private roof for charging electric mobility. The small system includes an E-scooter and a hydrogen car. For larger systems the transportation may include electric cars that frequently need to be charged.

a) E-scooter

The KTM E-Speed , from Upper Austria, has a capacity of 4.36 kWh and a range of 40 miles. For 5,600 km per year it takes **474 kWh** electricity to charge. From PV primary energy until the accumulator of the scooter is charged 80% remain.

b) E-charging station

According to enerChange GmbH from Innsbruck, who produce e-charging stations and plan e-infrastructure, including modular accumulator replacement systems. The charging station requires a capacity of 11 kW, and separate types of cables are used for different sizes of E-vehicles. 11 kW is nearly not possible for the small system to supply 11 kW, unless under super sunny conditions, but with 13 kW peak on the roof, and a fuel cell of only 2.6 kW, so that a smaller charging station, which will take longer, needs to be considered; one that can load the scooter in 3 hours, so about 2 kW.

c) Hydrogen car

Hydrogen cars take 1-1.5 kg H_2 per 100 km, pending driving style and use of on-board equipment. It takes 55.55 kWh to produce 1 kg H_2. At a mileage of 7,200 km annually, the electrolyser will require **4,000 kWh** to produce 72 kg of H_2, either filled directly into the car, or stored over Autumn and Winter, with the hydrogen for the fuel cell. Figure 4.3 right shows the nozzle of an H_2-Hyundai on sale as of 2014 (see Annex 11).

Figure 4.3 KTM E-scooter and nozzle of Hyundai FCEV *Source : KTM (2013), Hyundai (2013)*

Table 4.1 sums up the heating, electricity and transportation needs for a given year. The total useful energy (UE) requirement for the small system is **11,781 kWh** p.a.

Table 4.1 Energy services requirements by the small system *(own construction)*

Small System: 150 m²	ANNUAL	refer to
Space heating	6,480 kWh th	4.2.1 a)
Water heating	3,508 kWh th	4.2.1 b)
Cooling	540 kWh th	4.2.1 c)
Total heating & cooling	10,528 kWh th	

Electricity for heat pump	**2,807 kWh el**	4.2.2 a)
Electric appliances	**4,500 kWh el**	4.2.2 b)
Power for e- and H_2-mobility	**4,474 kWh el**	4.2.2 c)

E-scooter (5,600 km p.a.)	474 kWh p.a.	4.2.3 a)
Hydrogen car (7,200 km p.a.)	4,000 kWh p.a.	4.2.3 c)
Total annual requirement	**11,781 kWh p.a.**	

4.3 Weather data for the location Innsbruck

The source of the primary energy is the Sun. To obtain an overview of the location and to calculate the performance of the PV yield, as well as the heating requirement, weather data for Innsbruck was collected from the Central Institute for Meteorology & Geodynamics (ZAMG), the University Institute for Meteorology & Geophysics Innsbruck. Details are found in Annex 12. Table 4.2 is a summary. A 2008 study by BOKU predicts that average temperature in Tyrol may rise 5°C by end of the Century.

Table 4.2 Main weather parametres for Innsbruck as a location *(own construction)*

Average solar radiation	1,100 kWh/m² p.a.
Solar hours 2011	1,900 hours per year
Heating degree days average	3,311 Kd
Mean annual temperature	9.7°C
Ground water temperature	Mean 12°C

Table 4.3 mentions additional information such as air pressure, relevant to the fuel cell and hydrogen storage, as well as precipitation and snowfall, relevant to the PV yield.

Table 4.3 Additional weather parametres for Innsbruck *(own construction)*

Total precipitation per year	900 mm
Snowfall estimation	500 cm
Wind speed	up to 120 km/h
Mean air pressure	946 hPa
Humidity annual average	70.4%
Fine particles estimate	100 µm/m³

4.4 Photovoltaic and related installations

The purpose is to record the steps how the PV was dimensioned, including some reflections on the annual performance before arriving at the PV choice. Help was rendered by Elisabeth Reinthaler and Joaquin Hernandez from the Master's course with regard to calculating production, radiation, full load hours, performance ratio and kW peak. One of the online tools they suggested was PVGIS from the EU Joint Research Centre, Ispra, which is the main source of PV calculation also in Section 5.
In addition, the inverter and smart metre play a role as they reduce the useful energy.

a) Input data into PVGIS

According to the insolation angles in Annex 12, the tilt angle chosen for the PV is 35°. After several tries, **13 kW peak** were determined to be the appropriate dimensioning. Further variables entered into the online-tool on 7.9.2013 are recorded in Table 4.4.

Table 4.4 Input data for PV dimensioning in PVGIS-online tool; on 7.9.2013 *(own construction)*

Variable	**Choice**	**Comment**
the azimuth angle	10° West	horizontal dimensioning
radiation database	satellite-based data	old version based on statistical data
PV-type	crystalline silicon	several sources recommended this
position	"free-standing"	not building-integrated
tracking device	no	too costly

b) Dimensioning the PV for the small system

Dr. Kronberger (2011) wrote that 'total PV has to yield the total consumption demand plus the losses and related inefficiencies'. Bearing in mind that the annual requirement of 11,781 kWh has to be met, the PVGIS-tool calculated the following:

a) losses due to 'temperature and low irradiance' (8.0%)
b) losses due to 'angular reflectance' (2.8%).
c) In addition 16% system losses were self-defined.

This would have resulted in a total of 26.8%. PVGIS however stipulated the "Combined PV system losses" at 24.9% instead (see Annex 12), and in either case has already included such losses and, based on 13 kW peak, supplied the annual yield of 14,600 kWh; i.e. net of the above losses.
This figure may be seen as PE to satisfy the 11,781 kWh UE, but there are still the inverter and the smart metre that reduce the PE supplied resp. increase the UE demand.

c) Choice of PV manufacturer

The equipment chosen is shown in Figure 4.4 left and manufactured by Sunplugged in Schwaz. They specialise in thin-film and their products are found on curved surfaces. One module produces 102 W (+/- 5%), so for 13 kW peak up to 134 modules are used.

d) The inverter

The inverter is considered the heart of the system, as everything is connected to it. For the Case study an inverter by Fronius is chosen, the IG Plus 150 V-3. It has a direct current (DC) maximum input power of 12,770 W, and an alternative current (AC) nominal output of 12,000 W. From the PE of 14,600 kWh p.a., the inverter, due to it's max. efficiency of 95.9%, incurs a 4.1% reduction, leaving 14,001 kWh p.a. PE.

Figure 4.4 centre shows the IG Plus. In the future hybrid inverters may include smart metre features and storage functions, reducing equipment, and therefore resources.[2]

e) The smart metre

The smart metre is the brain of the system linking energy producers and energy users. The Smartfox metre by DAfi GmbH from Flachau/Salzburg requires 4 Watt to operate. The energetic analysis in Section 5.3 will go into the sequencing of the so-called relais, which are programmed by preference and depend on power supply, whether the Sun is shining or whether any of the storage means and fuel cell have to be resorted to.

A discussion was held on 30 August with the Sales Manager Mag. Wolfgang Goldner on the occasion of the builders' exhibition in Krems (Hausbaumesse 29.8.-1.9.2013) at their stand, together with a live demonstration. He explained that the Smartfox can be programmed to switch the relais in sequence; as one relais passes excess yield to the next relais until the entire system is satisfied. Final excess can be fed into the grid.

Figure 4.4 PV, inverter and smart metre *Source: Sunplugged, Fronius and Dafi GmbH (all 2013)*

[2] Comment by Mag. Rührlinger of Fronius on 2.9.2013 at a discussion in Wels.

4.5 Energy storage

Excess energy occurs when the Sun's rays are supplying more photons, which the PV is ready to convert, but the amount of all consumers in the circuit is below this amount. Up until now, most residential PV installations, and commercial ones too, are feeding excess solar energy into the grid and receive a subsidised feed-in tariff or market tariff.
More recently, the subsidised tariffs have been lowered, and a new trend with regard to storing the excess energy took place. This has been mainly done in the form of lithium-ion accumulators, and alternatives are lithium-iron-phosphate accumulators and lead gel batteries. All these methods store electric energy for a short period only.
More convenient types of storage are in the form of heat, if the tank is well-insulated, and gas, such as hydrogen. All three methods are to be considered in the small system.
References will be made to manufacturers in proximity to Tyrol due to practicality.

a) Short-term storage

The lithium-ion model Engion by Varta was explained in detail by Dr.Rudi Raymann and Mag. Heinz Bogner, of raymann photovoltaikanlagen gmbh, an installation company in Deutsch-Wagram, at the Bauen & Energie Wien-fair on 22 February 2013.
Figure 4.5 left shows that the Engion Family Plus-model is set up on a modular system.
For 8.3 kWh 18 units are needed, while a capacity of 13.8 kWh will fill the entire case.
At an efficiency of 95%, if used all year long, it would reduce the PE to 13,300 kWh.

b) Heat storage

In the hotel in Steyr (Section 3.2.4) two tanks were used, one for pre-heating and the other for process water. For the 300 litre buffer tank required by the small system, the Trivalent-model from Sun-Systems (Figure 4.5 right) in Wörgl was taken. Connected to it are circulation pump and heat exchanger that consume energy at 300 W and 60 W resp. The heat exchanger reduces the number of degrees the tank needs to be heated.

Figure 4.5 Engion Family Plus and buffer storage *Source: Varta Storage, Sun Systems (both 2013)*

c) Electrolysis and hydrogen storage

According to Fronius, during Summer roughly 500 PV hours can be harvested for hydrogen production, which at an electrolysis rate of 1.2 Nm^3/h equals 600 m^3, at standard temperature and pressure. The electrolyser by Fronius is a high pressure-electrolyser, meaning that as the hydrogen gas is produced, it is already at 150 bar. Key is that the electrolyser runs full cycles as is common knowledge with batteries. Short radiation interruptions (like a cloud) can be bridged by the lithium-ion battery. As mentioned in Section 3.3.3 b) the 12 bundles of four cylinders each (Figure 4.6 left) can hold 480 m^3 at 200 bar; Fronius (2013). The number of cylinders can be varied according to need.

4.6 PEM fuel cell for a single-family home

Fronius are constructing a “House of the Future”, where the primary energy source is the Sun. Electricity from photovoltaic installation is supplied to the house as well as to a heat pump and a buffer storage. Excess energy can a.o. charge batteries for providing energy at night, but also runs an electrolyser to produce hydrogen as storage for longer periods, then use it as the fuel in a fuel cell. This concept shall be taken as a basis for the energetic calculation in Section 5 in order to explore the potential.

Discussions with persons from Fronius have taken place at the Intersolar exhibition in Munich on 20 June, 2013, and also on 2 September, 2013 in the headquarters in Wels.

Fronius has built the stationery cell and the portable cell, and the new cell incorporates the electrolyser in one casing. This saves materials, therefore resources, and space. The 25F has a max. power of 2 kW and the new Energy Cell will feature 2.6 kW. Figure 4.6 right shows the current fuel cell 25F-model without the built-in electrolyser.

Figure 4.6 Hydrogen storage and fuel cell 25F-model *Source: Fronius (2013)*

5. Energetic analysis of the fuel cell

The theoretical basis for the calculation of the fuel cell's efficiency was delivered in Section 3.2.1 and the practical aspect is provided by Section 4 based on the Case study. The energetic analysis first considers the fuel cell's efficiency, followed by the overall electrical efficiency of the small system, Section 5.1, then matches the PV yield (Section 5.2) to the consumption (Section 5.3) incorporating model days (Section 5.4). Excess may be fed to the grid (Section 5.5). Additional equations are in Annex 15.

5.1 Energetic efficiency calculation input

The significance of calculating the efficiency is to establish how much PE had to be obtained, and how much UE came out, particularly with regard to the storage aspect. Therefore two main equations, already introduced in Section 2.2, shall be broken down into constituents, leading to further equations to do with thermodynamics and kinetics.

5.1.1 Fuel cell efficiency

As in Section 2.2.1, the **fuel cell efficiency of 36%** is calculated based on Uni Münster, ZSW (2001), Larminie (2003), Kurzweil (2013), Lin (1999), and Walkowiak (2005).

$$\eta_{FuelCell} = \eta_{Therm} * \eta_{Volt} * \eta_{Curr} * \eta_{Aux} \quad (1)$$

$$[= 0.8296 * 0.4878 * 0.9491 * 0.9473 * 100]$$

a) Thermodynamic efficiency [η_{Therm}]

The reversible potential of the energy output [ΔG] is divided by the enthalpy[3] [ΔH], the higher heating value of water (as water remains in the liquid form for temperatures under 100°C) at standard state (i.e. 25°C or 298 K and 1 bar pressure) for 1 mol H_2O.

$$\eta_{Therm} = \Delta G / \Delta H \quad (7)$$

ΔH at the higher heating value is -285.83 kJ/mol and at the lower heating value equals -241.8 kJ/mol, referenced by Schroeder's table of thermodynamic properties, provided by Nave (2013) of Georgia State University. According to Nave "the process must provide the energy for the dissociation plus the energy to expand the produced gases.
The "negative" sign indicates that energy is being released, i.e. an exothermic reaction.

[3] Enthalpy (Greek) is the potential energy due to volume, pressure and temperature in a given system. It is measured as the heat content of a (chemical) gas resp. the ability to do work in correspondence to the amount of its mass; such as per kJ/kg.

ΔG is referred to as Gibbs free energy, after Josiah Willard Gibbs (1839-1903), which is the energy the fuel cell has to bring up, i.e. the reversible potential, to achieve the enthalpy ΔH. The difference between ΔG and the enthalpy is the entropy, supplied by the environment pending atmospheric pressure and temperature, denoted as TΔS; T is the temperature change expressed in Kelvin and ΔS the energy content per degree K.

$$\Delta G = \Delta H - T\Delta S \qquad (8)$$

Entropy refers to the Second Law of Thermodynamics Milics and Neményi (2008) and is the unavailable work which the system produces but cannot use. From Kurzweil (2013) the equation for ΔS is given by subtracting energy quantities of H_2 and of half-O_2 from that of H_2O (water). Values of 1 mole are provided by Schroeder's table.

$$\Delta S = H_2O - H_2 - ½O_2 \qquad (9)$$

Table 5.1 summarises the above equations and renders a thermodynamic efficiency of 83%. If the lower heating value were used, at -241.8 kJ/mol, then 94% would result.

Table 5.1 Calculation of thermodynamic efficiency *(own construction)*

ΔS	$H_2O - H_2 - ½O_2$	1*69.91 – 1*130.68 – 0.5*205.14 [in J/K]	-163.34 J/K
T		25°C expressed in Kelvin	298 K
TΔS		multiplication	48.7 kJ/mol
ΔH		from Schroeder's table	-285.83kJ/mol
ΔG	ΔH - TΔS	-285.83 kJ - (-48.7 kJ)	-237.13 kJ/mol
η_{Therm}	**ΔG / ΔH**	**(-237.13 / -285.83) * 100**	**82.97%**

Figure 5.1 shows the above principle with TΔS of 48.7 kJ/mol as the entropy.

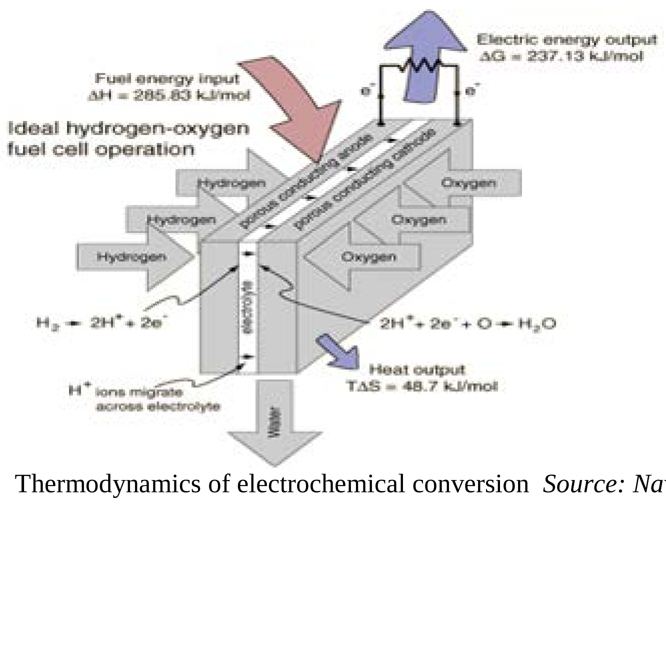

Figure 5.1 Thermodynamics of electrochemical conversion *Source: Nave (2008)*

b) Voltage efficiency [η_{Volt}]

Voltage is a measure of electric potential (or electromotive force) based on Newton-metre per Coulomb, later also as Watt per Ampère, or Ampère times Ohm. The voltage efficiency measures the spectrum of the cell's potential depending on the resistance of the circuit (Ohm); Uni Münster. It was seen in Figure 3.3 that the polarization curve opens with the maximum reversible potential of the fuel cell [E_{rev}], and ends when the resistance is so great that it does not permit the flow of any electrons anymore [E_{actual}]; like a quantity.

See Annex 13 for various units with regard to electrochemistry, and as a background.

$$\boldsymbol{\eta_{Volt} = E_{actual} / E_{rev}} \tag{10}$$

The maximum possible voltage based on 1 mole of hydrogen involves the Faraday constant F multiplied by the number of atoms in a mole, which for hydrogen is two. ΔG was already given by equation (8). Joules divided by Coulombs will equal Volt.

$$\mathbf{E_{rev} = - \Delta G / nF} \tag{11}$$

E_{actual} is the terminal voltage at the cathode, according to Lin (1999, p.89), also described by Larminie (2003, p.22) as the "operating voltage" of a fuel cell, which is taken usually between 0.6 and 0.7 V.

In Fronius' 25F-model the capacity of 2 kW at an output current of 82 A rendered a voltage of 24 V, and since the stack consists of 40 cells, the single cell's operating voltage amounts to 0.6 V.

For the new Fronius model at 2.6 kW, 48 V and output current 54 A however, the number of cells is not known. Therefore 0.6 V shall be assumed as a benchmark value.

Table 5.2 records the calculation for the voltage efficiency.

Table 5.2 Calculation of voltage efficiency *(own construction)*

E_{rev}	- ΔG / nF	-237.13 kJ/mol / -(2 * 9.649 * 10^4) -237,140 J / 192,980 C	1.23 V
E_{actual}		based on Fronius' old model	0.6 V
η_{Volt}	**E_{actual} / E_{rev}**	**0.6 / 1.23 * 100**	**48.78%**

Given that the fuel cell needs some electricity of it's own, later on in the Model Days' calculations, 2.5% shall be deducted from the electric production of the fuel cell.

c) Current efficiency [η_{Curr}]

The current efficiency is the actual current of the cell divided by the maximum current.

$$\eta_{Curr} = I_{act} / I_{max} \quad (12)$$

According to Faraday, the current efficiency is limited to the electric current I expressed as the current density i on a given surface area (measured in A/cm²) at a particular time interval t at a specified temperature T, by applying the gas constant R. For the current density, which is the only value in this equation which is not generic, the total area of one cell from the 25F-model (400 cm²) is divided by the output current 82 A, where fore the new model the output current is known, but the number of cells.

$$I_{act} = R * i * T * t \quad (13)$$

The maximum current possible is defined by the Faraday constant F, the number of atoms per mole z, and the respective standard pressure p.

$$I_{max} = F * p * z \quad (14)$$

Table 5.3 records the calculation for the voltage efficiency of the above equations.

Table 5.3 Calculation of current efficiency *(own construction)*

I_{act}	R * i * T * t	8.314 * 0.21A/cm² * 298K * 356s	185,223
I_{max}		9.649×10^4 1.0113Pa * 2	195,150
η_{Curr}	**I_{act} / I_{max}**	**185,223 / 195,150) * 100**	**94.91%**

d) Efficiency of the auxiliary equipment [η_{Aux}]

The more valves, pumps and pipes there are, the more losses and corrosion await. At the same time, the auxiliary equipment also contributes useful gains through it's heat.

$$\eta_{Aux} = \sum_{Heat,Aux,Gains} / \sum_{Therm/Phys,Aux,Losses} \quad (15)$$

Table 5.4 shows the gains and the losses as broad estimations from various sources.

Table 5.4 Calculation of auxiliary equipment efficiency *(own construction)*

Gains	$\sum_{Heat,Aux,Gains}$	estimations	90%
Losses	$\sum_{Therm/Phys,Aux,Losses}$	estimations	95%
η_{Aux}	$\sum_{Heat,Aux,Gains} / \sum_{Therm/Phys,Aux,Losses}$	90% / 95%	**94.74%**

5.1.2 System efficiency

As mentioned in Section 2.2.2, the **system efficiency is equal to 18%** and is based on an own construction based on the preliminary input of the Case study, i.e. the system.

$$\eta_{System} = \eta_{PV} * \eta_{Inverter} * \eta_{E\text{-}lys} * \eta_{H2\text{-}Stor} * \eta_{FuelCell} \quad (2)$$

[= 0.732 * 0.960 * 0.822 * 0.850 * 0.364 * 100]

a) PV losses [η_{PV}]

The efficiency of photovoltaic cells is widely claimed as being approx. 14%. Though how can it affect the yield when the Sun's energy is so immense. The PVGIS-tool factored in losses due to 'temperature variation, low irradiance and angular reflectance' (Section 4.4), as also transmission losses from cables and "other" losses. These amounted to 26.8%, and therefore η_{PV} is the theoretical remainder at 73.2%.

b) Inverter [$\eta_{Inverter}$]

The DC to AC-conversion can reduce the voltage by around 4%, thus $\eta_{Inverter}$ is 96%.

c) Electrolyser efficiency [$\eta_{E\text{-}lys}$]

According to Stolten (2012), the efficiency is defined by the ideal voltage of the higher heating value V_{HHV} (liquid water), divided by the actual electrolyser voltage $V_{E\text{-}lys}$. The result proves that the lesser energy is put in, the better the efficiency. Thermodynamically electrolysis is the reverse of the fuel cell; see further in Annex 15.

$$\eta_{E\text{-}lys} = V_{HHV} / V_{E\text{-}lys} \, [\%] = 1.48 \text{ V} / 1.8 \text{ V} = 82.2\% \quad (16)$$

s) Hydrogen storage [$\eta_{H2\text{-}Stor}$]

The loss of storage is mainly due to the compression of the gas, which in the case of a high pressure-electrolyser may be omitted. However, Lin (1999, p.142) argues that the "amount of work required to compress the hydrogen gas into the cylinder means that there is an energy penalty of approximately 5-10%". To be conservative, 15% will be counted, rendering the efficiency of the storage at $\eta_{H2\text{-}Stor}$ equal to 85%.

Short-term storage is not considered in the above. If it were, then the accumulator's efficiency of 95% (Section 4.5) would reduce the system efficiency to 17%. Also, the gains of the heat exchanger and the water buffer tank are debatable; see Annex 16.

5.2 Photovoltaic yield of 13 kW peak in Innsbruck

Based on 13 kW, Figure 5.2 shows the annual yield (blue line) resulting in 14,600 kWh after losses. The black line refers to a tracking device which even reaches 18,000 kWh p.a. Additional tracking options are not considered for the purposes of assessment.

The data is based on statistics, which say nothing about the weather nor any global radiation in the future. And, the tracker is too costly for the small system. Investing in additional panels would augment yield, but incur more resources being exploited.

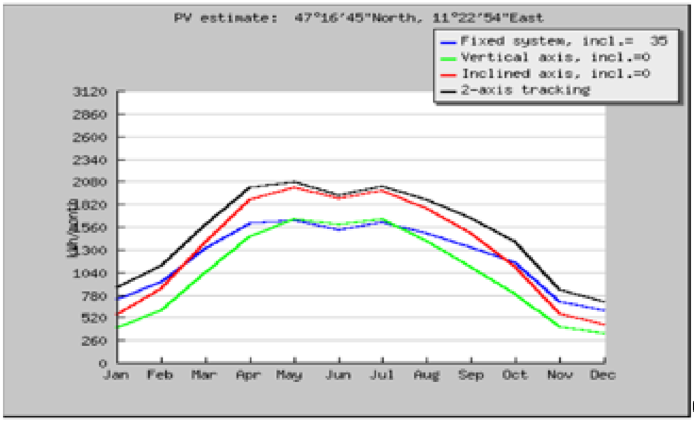

Figure 5.2 12-months PV yield of the small system *Source: PVGIS (2013)*

5.3 Energy consumption of the small system

The energy consumers need 11,781 kWh on annual basis. To define Model Days (Section 5.4), the consumers are separated into 6 categories of relais functions of the smart metre, plus a seventh for the grid, which are outlined in Table 5.5, and quantified in Annex 17. $E_{\sum}$ is the sum of electricity supply required by the consumers which theoretically can amount to 55.55 kWh, but realistically is closer to 5.31 kW, though a big difference may be experienced when sufficient Sun allows the electrolyser to run.

$$\mathbf{E}_{\sum} = \mathbf{E}_{\mathbf{Base}} + \mathbf{E}_{\mathbf{House}} + \mathbf{E}_{\mathbf{Priv}} + \mathbf{E}_{\mathbf{Support}} + \mathbf{E}_{\mathbf{Temp}} + \mathbf{E}_{\mathbf{Guest}} + \mathbf{E}_{\mathbf{Grid}} \quad (17)$$

Table 5.5 Smart metre sequencing functions *(own construction)*

Relais	Description	Theoretic	Realistic
$\mathbf{E}_{\mathbf{Base}}$	base load of the system, absolute minimum that constantly runs	0.9 kW	0.9 kW
$\mathbf{E}_{\mathbf{House}}$	all household-related activity including kitchen and bathroom	10 kW	1.15 kW
$\mathbf{E}_{\mathbf{Priv}}$	hobby- and pastime-related items, incl. computer, TV and radio	3.74 kW	0.1 kW
$\mathbf{E}_{\mathbf{Support}}$	storage-related and standby-functions (buffer tank, li-on battery)	4.11 kW	1.11 kW
$\mathbf{E}_{\mathbf{Temp}}$	pre-programmed washing machines and charging of E-mobility	23.8 kW	2.0 kW
$\mathbf{E}_{\mathbf{Guest}}$	a small contingency for visitors to charge E-bike or smartphone	2 kW	0.05 kW
$\mathbf{E}_{\mathbf{Grid}}$	optional feed-in due to excess that cannot be stored any further	11 kW	

5.4 Model days of PV, storage and fuel cell activity

The PVGIS-tool rendered average days with three different types of skies; the red line being a very idealistic sky, the blue line a realistic sky, and green line a diffuse sky. Figure 5.3 and Table 5.6 show the average yields in July, December and March.

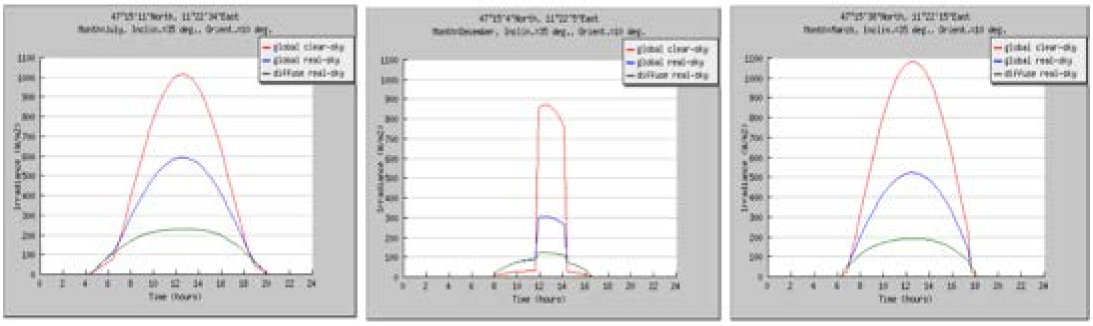

Figure 5.3/Table 5.6 Average daily irradiance (W/m²) in July, December and March *Source: PVGIS (2013)*

(in W/m²)	*Reference month*	*"idealistic sky" (red line)*	*"realistic sky" (blue line)*	*"diffuse sky" (green line)*
"Summer"	July	1,000	600	220
"Winter"	December	870	300	120
"Spring/Autumn"	March	1,080	510	200

a) Model Day I "direct PV"

On a day of realistic sky, the irradiance on Innsbruck (600 W/m² in July, 300 W/m² in December and 510 W/m² in March resp.) is converted by 13 kW PV into 7.8 kW and 3.9 kW and 6.63 kW resp. Table 5.7 shows the first six relais with realistic activity, each passing on the surplus energy, i.e. beginning with Summer, relais E_{Base} (i) is satisfied with 0.9 kW and passes on the remainder of 6.9 kW to relais E_{House} (ii) which takes 1.15 kW and passes on 5.75 kW to relais E_{Priv} (iii), and so on. The 600 W/m² of July and the 510 W/m² of irradiance in March, as examples, indicate that the capacity as required by the relais can be supported by the PV. However, the 300 W/m² in December is insufficient for the PV to satisfy all of the relais, as the 5th and the 6th fall short, with the consequence that one storage means would already have to be activated.

Table 5.7 Model Day I under realistic sky conditions *(own construction)*

(1st column in W/m² resp. rest in kW)	*global real-sky*	*PV yield (kW)*	*E_{Base} (i) 0.9*	*E_{House} (ii) 1.15*	*E_{Priv} (iii) 0.1*	*$E_{Support}$ (iv) 1.11*	*E_{Temp} (v) 2.0*	***E_{Guest}** (vi) 0.05*	***Total 5.31 kW***
"Summer"	600	**7.80**	6.9	5.75	5.65	4.54	2.54	2.49	**2.49**
"Winter"	300	**3.9**	3	1.85	1.75	0.64	-1.36	-1.41	**-1.41**
"Spring/Autumn"	510	**6.63**	5.73	4.58	4.48	3.37	1.37	1.32	**1.32**

b) Model day II "excess to be stored"

Table 5.8 first identifies the demand of the small system divided into heating, electricity and mobility on monthly basis. Space heating was accorded with 2012 HDDs, and water heating matched to the fluctuations of the ground water temperature.

Table 5.8 Monthly heating, electricity and mobility demand of the small system *(own construction)*

(in kWh th)	*Space Heating*	*Water Heating*	*Cooling*	*Sum*	*Heat pump*	*Electricity*	*Mobility Electric*	*Mobility Hydrogen*	*(in kWh el)*
Pre-Sum	6,480.0	3,508.0	540.0	10,528.0	2,807.0	4,500.0	474.0	4,000.0	11,781.0
January	1,232.2	233.9		1,466.1	391.0	375.0	39.5	333.3	1,138.8
February	1,332.6	300.7		1,633.3	435.6	375.0	39.5	333.3	1,183.4
March	739.3	300.7		1,040.0	277.3	375.0	39.5	333.3	1,025.2
April	552.6	367.5		920.1	245.4	375.0	39.5	333.3	993.2
May		367.5		367.5	98.0	375.0	39.5	333.3	845.8
June		367.5		367.5	98.0	375.0	39.5	333.3	845.8
July		367.5	270.0	637.5	170.0	375.0	39.5	333.3	917.8
August		300.7	270.0	570.7	152.2	375.0	39.5	333.3	900.0
September		300.7		300.7	80.2	375.0	39.5	333.3	828.0
October	607.1	233.9		841.0	224.3	375.0	39.5	333.3	972.1
November	843.4	183.8		1,027.2	273.9	375.0	39.5	333.3	1,021.8
December	1,172.1	183.8		1,355.9	361.6	375.0	39.5	333.3	1,109.4
Post-Sum	6,479.4	3,508.0	540.0	**10,527.4**	2,807.3	4,500.0	474.0	4,000.0	**11,781.3**

Next, Table 5.9 builds on the above and incorporates the PV input on the left side, compared to the requirements on monthly basis on the right side. The "Monthly surplus"-column is the long-term storage potential. The total surplus of 4,300.8 kWh less the total deficit 1,512.52 kWh results in a net surplus of 2,788.29 kWh. As said in Section 3.3.3 b), one full H_2-storage requires 1,440 kWh. Theoretically the net surplus would nearly reach twice this capacity of the total hydrogen storage volume.

Table 5.9 Monthly PV yield vs. consumption, with resulting surplus resp. deficit for storage *(own construction)*

(in kWh/m²)	*Global radiation (daily)*	*Global radiation (monthly)*	*PV yield (daily)*	*PV yield (monthly)*	*Average daily demand*	*Monthly demand*	*Monthly surplus*	*Monthly deficit*	*(in kWh el)*
Preliminaries						11,781.0			*1,440.0*
January	2.2	68.8	23.3	722.3	36.7	1,138.8		- 416.5	
February	3.2	89.0	32.9	921.2	42.3	1,183.4		- 262.2	
March	4.2	131.4	42.3	1,311.3	33.1	1,025.2	286.1		*20%*
April	5.4	163.2	53.1	1,593.0	33.1	993.2	599.8		*42%*
May	5.6	173.0	52.9	1,639.9	27.3	845.8	794.1		*55%*
June	5.4	161.4	50.7	1,521.0	28.2	845.8	675.2		*47%*
July	5.6	172.1	51.8	1,605.8	29.6	917.8	688.0		*48%*
August	5.1	157.2	47.9	1,484.9	29.0	900.0	584.9		*41%*
September	4.6	137.4	44.3	1,329.0	27.6	828.0	501.0		*35%*
October	3.7	115.0	36.9	1,143.9	31.4	972.1	171.8		*12%*
November	2.3	67.8	23.3	699.0	34.1	1,021.8		- 322.8	
December	1.9	58.3	19.3	598.3	35.8	1,109.4		- 511.1	
Post-Sum		1,494.6		**14,569.6**		**11,781.3**	**4,300.8**	**- 1,512.5**	***2,788.3***

c) Model day III "fuel cell providing energy"

There are essentially four different scenarios when the fuel cell is being implemented:

a) the household cannot be satisfied by PV alone, the fuel cell recharges the battery.
b) If the battery is depleted, the inverter will connect the cell directly to the appliances.
c) If new PV yield is gained at the time of fuel cell action, the battery will be charged.
d) Heat, as a form of pure energy, is supplied as by-product from the fuel cell as well.

In Table 5.10 the objective is to lay out the energy producers against the energy users. The columns "per day" show the maximum kilowatt hours deliverable from the "input" positions and consumed by the "output" positions. The columns "max. supply" denote the capacity at any given moment which the fuel cell and other energy supply can give. The fuel cell does not store energy, like a common battery, but it receives the "fuel". The H_2 can be sourced from the cylinder storage or the car's tanks interchangeably.

Table 5.10 Maximum input vs. output per day and size in kW to compare supply and demand *(own construction)*

Hours	Ratio	**INPUT**	per day	max. supply	**OUTPUT**	per day	max. demand	Ratio	Hours
8	1	PV	104.00	13.00	E_{Base}	21.6	0.9	1	24
2.2	0.95	Li-on	8.36	4.00	E_{House}	6.00	10.00	0.3	2
1	0.25	Buffer tank	3.92	15.66	E_{Priv}	7.48	3.74	0.25	8
24	0.38	Fuel cell	23.71	2.60	$E_{Support}$	14.80	4.11	0.9	4
1.5	0.65	H2-car accu.	23.40	24.00	E_{Temp}	71.40	23.80	0.6	5
3.4	0.65	e-scooter	4.42	2.00	E_{Guest}	4.00	2.00	0.5	4
		Total	**167.81**	*61.26*		**125.28**	*44.55*		
		no PV	*63.81*	*48.26*		*42.53*			

5.5 Feeding excess into the public grid

To sell the excess, which is beyond own usage and storage, to the grid operator, is only possible in Tyrol for PV with up to 5 kW peak. The feed-in-tariff is 15 cents/kWh. Table 5.11 is only a theoretical approach with regard to 13 kW peak, i.e. how much absolute excess could be (would be advisable) to feed-in. The result is: on 123 days.

Table 5.11 Number of days per month and hours of feeding in versus kW-capacity to feed in *(own construction)*

	Daily Glob. Rad.	*Daily PV yield*	*Daily demand*	*Daily excess*	*Daily fed in*	*Days per month*	*Days fed in*	***kWh***
units	*kWh/m²*	*kWh*	*kWh*	*kWh*	*kWh*	*d*	*d*	*kWh*
April	5.44	53.1	33.1	20.0	15.0	30	17	**255**
May	5.58	52.9	27.3	25.6	20.0	31	26	**520**
June	5.38	50.7	28.2	22.5	16.0	30	22	**352**
July	5.55	51.8	29.6	22.2	17.0	31	30	**510**
August	5.07	47.9	29.0	18.9	13.0	31	28	**364**
Year					*16.3*		123	**2,001**

6. Ecological analysis of a fuel cell life cycle

This Section applies the Lifecycle Assessment (LCA)-model as developed by the International Organization for Standardization, Geneva in 2006, and Section 6.2 follows the four categories in accordance with the ISO-codes, with the fuel cell as the functional unit. Section 6.3 approaches the system from an environmental view.

6.1 Own definition of the terms "ecology" and "ecological"

"Ecology" and "ecological" have to do with the World we live in, and the prefix "eco", commonly associated with the environment, in Greek actually means "house" (οἶκος). So if this World were to be the "house", it would be a rather big house. Ultimately, the term "ecological" seeks to include an order of completeness, wholeness, entirety. Significant for the fuel cell are these three propositions, that shall guide this LCA:

a) fuel cells can process stored energy and deliver it to meet useful energy demands
b) the fuel cell had to be constructed first, and the hydrogen derived, e.g. from water
c) at the end of it's lifetime the fuel cell will not function anymore, but will still exist.

6.2 Lifecycle assessment of the fuel cell applied

Most Lifecycle Assessments (LCA) conducted in the area of hydrogen and fuel cells relate to fuel cells deriving hydrogen from natural gas, i.e. including a reformer, and emitting more greenhouse gases than the hydrogen derived from renewable sources such as wind, PV and hydro power. Then, only the manufacturing of the primary energy sources is responsible for carbon emissions and exploitation of raw materials. Also, LCA studies that look at PEM fuel cells, as opposed to SOFC, molten-carbonate FC (MCFC) and alkaline FC (AFC) focus on mobile applications such as fuel cell cars. Therefore, for a first attempt of assessment, various data are scrambled and assembled.

6.2.1 "Goal and scope definition" (ISO 14041)

a) The functional unit

The functional unit, as per Masoni (2011) is the fuel cell by Fronius as in Section 4.6, and is quantified by it's exergy (sum of electrical and thermal energy), in Mega Joules:

$$\mathbf{MJ_{exergy} = MJ_{el} + \varsigma_{th} * MJ_{th}} \qquad (18)$$

According to Masoni (2011) the thermal energy is factored by ς_{th}, equal to integer 1 less the quotient of ambient temperature T_a by mean temperature T_m, (a carnot-principle).

$$\varsigma_{th} = 1 - (T_a / T_m) \qquad (19)$$

Table 6.1 summarises the functional unit as having a lifespan of 10,000 hours, the power it consumes may be roughly 2.5% of the power it produces, Fronius' 25F-model has a weight of 125 kg, is stationery, and has an exergy of 6,550.26 MJ over 20 years.

Table 6.1 Calculation of the exergy of the functional unit Fronius 25F *(calculation of Masoni-formula)*

MJ el	hours of lifetime	h		10,000
	power	kW el		2
		kWh		20,000
	conversion	MJ	*3.6*	5,555.56
Carnot	integer			1
T a	ambient temp.	K		298.15
T m	mean temp.	K		353.13
				0.84
ς th		factor		0.16
MJ th	hours of lifetime	h		10,000
	heat	kW th		2.3
		kWh		23,000
	conversion	MJ	*3.6*	6,388.89
ς th * MJ th				994.71
MJ exergy				6,550.26

b) The goal

The goal is two-fold. First, to learn about the input and output of the fuel cell in terms of operation, as well as the lifetime from manufacturing until recycling and disposal. Secondly, this LCA shall identify areas that may be improved and further researched.

c) The scope

The scope extends to the reference flow of the functional unit in terms of manufacture, not in terms of providing energy service, i.e. PV, electrolyser, lithium-ion accumulator and other devices are outside of the boundary, and will be addressed in Section 6.3.

d) The data

The data is generally based on the scientific work by the authors listed in Section 2.3.

6.2.2 "Inventory analysis" (ISO 14041)

a) Process of the functional unit

One hour of operation of a PEM fuel cell using hydrogen gas as the fuel, consumes 130 grams of hydrogen and 990 grams of oxygen (derived from 4.8 kg of air, and pending the stoichiometry of oxygen),. The input is also 50 Watt of electricity to keep the cell running, and atmospheric pressure at the temperature of the environment.
Table 6.2 summarises the various input items into the fuel cell on the left-hand side.

Table 6.2 Input and output of a PEM fuel cell for the duration of 1 hour *(own construction)*

Into the Fuel Cell		**Out of the Fuel Cell**	
Electricity	50 W (0.05 kWh)	2 kWh el	Electric energy
Hydrogen	0.13 kg/h	1.12 kg/h	Water
Oxygen	0.99 kg/h (from ca. 4.8 kg/h air)	2.3 kWh th	Heat
Atmospheric pressure	1 bar	48.7 kJ/mol	Entropy
Temperature	25°C	80°C	Temperature

Figure 6.1 Fronius 25F

The output corresponding to the above input for one hour, is shown on the right-hand side of Table 6.2 and is detailed in Annexes 14 and 15. Electric output of 2 kWh el is complemented by the heat output (2.3 kWh th) and the by-product of 1.12 kg H_2O, and the temperature has risen to 80°C; the noise is said to be around 60 db (similar to a conversation); FuelCells (2013). Table 6.3 is an extrapolation to 500 hours per year and the lifetime.

Table 6.3 Input and output of a PEM fuel cell for 500 hours and 20 years *(own construction)*

Into the Fuel Cell		**Out of the Fuel Cell**	
500 hours (1 year)	10,000 h (20 yrs)	**500 hours (1 year)**	10,000 h (20 yrs)
25 kWh, 65 kg H_2 , 495 kg oxygen, 2,400 kg air	500 kWh, 1,300 kg H_2 , 9,900 kg oxygen, 48,000 kg air	**1,000 kWh el, 1,150 kWh th, 560 kg water**	20,000 kWh el, 23,000 kWh th, 11,200 kg water

Naturally, the extrapolated figures are in the ideal case. And it remains to be seen by real life-example, what the actual input and outcome of operating the fuel cell entails.

b) Production of the functional unit

Data could be obtained by identifying the energy consumption of excavation and mining processes of the raw materials and metals which are used in a fuel cell. As per Section 3.2.2 the main solids used are platinum, fluorine, graphite and carbon. According to Pehnt (2001), the mining of platinum group metals, including palladium, rhodium and ruthenium as alternatives to platinum (e.g. in South Africa) causes emissions of sulphur oxide (SO_2) and nitric oxide (NO_x), which are said to cause acidification. Also, graphite (e.g. in China) incurs "160 MJ of non-renewable energy resources per kg graphite [produced]". The tetrafluoroethylene polymer membrane (Nafion™) follows a lengthy process of "production of the monomer, the polymerization, the liquid-solid extraction, drying and reaction with SO_3 in organic solvents". These and other substances require energy to be mined, they will be transported (thousands of kilometres) and treated further, before being delivered to the fuel cell manufacturer or other trading houses in between. But they also bring jobs.

In the manufacturing stage, the total electricity bill could be divided by number of units of fuel cell and components produced. The same would be the case for all sub-suppliers. Furthermore, to measure the energy that went into producing the main and sub-components has to include losses due to the limited efficiency. The total number of factories and the number of different countries then give a measure of magnitude. Annual electricity consumption of each manufacturer, and dividing it by the number of the functional unit, was also proposed by van Rooijen (2006).

c) End-of-life

After the fuel cell's useful life, it may still run at a lesser efficiency, but the membrane at some point will not be able to fulfil it's function any longer, i.e. it will stop working. While new concepts are being developed to exchange the membrane on regular basis, Staffell & Ingram (2010) reported about modelling 'disposal'. They cite the Waste Electrical and Electronic Equipment Directive (2012/19/EU) where the returning of stacks may be incentivised.

Staffell & Ingram (2010) claim that in reality only 50% of returned platinum is being recycled, although it would be assumed that fuel cells returned to the manufacturer would result in a high percentage (above 90%) of "the majority of the fuel cell stacks" to be dismantled and recycled due to the high value of the components, whereas the balance of plant would remain at 50% “due to their lower scrap value”.

A word on steel: they make reference to the 65:35 ratio of steel, meaning that it takes 1.54 kg of steel for 1 kg used in the product. The difference of 0.54 kg is reused. After the fuel cell is returned, out of 1 kg steel 0.74 kg are reported to be recycled. This means that every 2 kg steel of returned fuel cells contribute with 1.48 kg recycled steel.

6.2.3 “Impact assessment” (ISO 14042)

Global warming potential is based on characterising emissions of Cd, CO_2, NO_x, SO_2 etc. that are measured against their output due to the production of the functional unit. While in Pehnt (2001) CO_2- and CH_4- and N_2O-emissions can be found, his functional units consisted of 75 kW el and 275 kW el, and cannot be applied here. It is important to note that CH 4 has a factor 23 against CO_2, and N_2O even 296x. NO_x, NH_3 and HCl are also measured in equivalents of SO_2, one of the main incumbents of acid rain; Schwaiger (2012). Extrapolating such figures in reverse for the 2 kW functional unit would be ambiguous. However, Figure 6.2 does show the proportional contribution of the components to the consumption of energy resources, global warming and acidification. Gas diffusion electrodes (GDE) take the 74%-share in the acidification, and the carbon fibre in the flow field or bipolar ‘plates’ take the 30-share in the emissions (global warming).

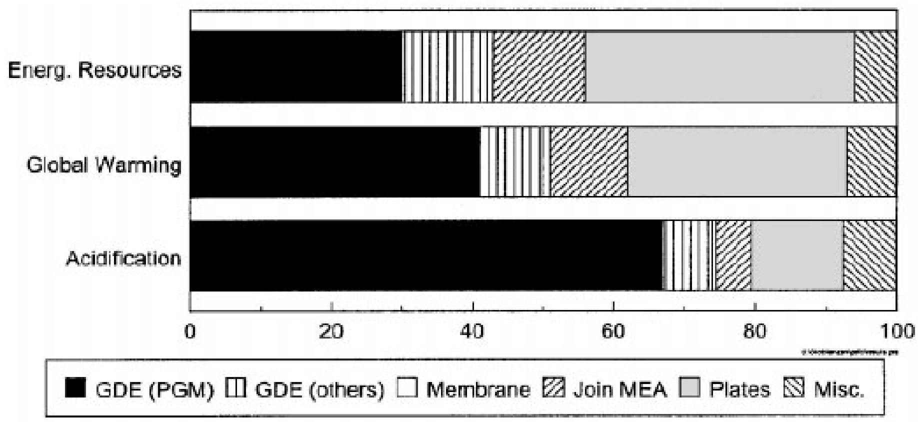

Figure 6.2 Contribution of stack components to emissions and acidification *Source: Pehnt (2001)*

6.2.4 “Interpretation” (ISO 14043)

Sofar, not so many LCAs have been performed on PEM fuel cells, and mainly focussed on mobile applications. Residential fuel cells analysed were mostly of the SOFC-type.

The not-so-good news is that carbon- and graphite-related components prove the highest impact on global warming and acidification, not to mention ecotoxity, and the good news is that, although platinum is cumbersome to attain, the processing itself uses low energy. Another positive aspect is that at least 50% of the fuel cell are being recycled, at the expense of additional energy input. This in mind, it supports the case, as will be addressed in Section 7, that fuel cells in private residential use, or in communal and commercial stationery use, should not be owned by the consumers, but to be owned and run and renewed by specialised third parties to be detailed further on.

For a future environmental analysis of this type or similar, more data shall be obtained from manufacturers and suppliers in question. A general trend to more transparency, e.g. by way of corporate social responsibility (CSR)-reports has been noticed going on. The above data is neither complete, nor precise, but it is under the circumstances of this paper to be seen as a rudimentary basis to engage in further dialogue with industry. Normalisation and other models have not been applied, because the data is too scarce. Therefore completeness checks, sensitivity checks have to wait for more precise data. Data from the scientists' work, as quoted and referenced, is taken as a rough indication.

For a further analysis, the topic to look out for specifically is that of waste treatment, recycling processes, production networks among sub-suppliers and their respective efficiency, environmental conscience, and ultimately to reuse the fuel cell completely.

One recommendation that does not flow directly out of the above points raised, is the continued need for norms and standardisation of the production of fuel cells. The norms may be as profane as having the same size of cables, connectors and plugs, and the reasons for it may be more economic. But the standardisation of fuel cell components with regard to lifetime and interoperability and to maybe be exchanged, rather than renewing the entire fuel cell after the end-of-life, can help manufacturers to save material, and their sub-suppliers to produce longer-lasting equipment.

6.3 Considerations on the system as a whole

By way of logic and as defined in the term “ecological”, the whole system has to be considered but would be beyond the scope of this paper. Suffice it to say, that separate LCAs have been conducted on PV, short-term storage and other related processes. More importantly, with regard to fuel cells and hydrogen, the method of hydrogen production, particularly in residential and communal arrangements, as well as commercial buildings, depends so much more on the activities carried out at the premises and the type, amount and quality of useful energy required. Private homes in future may see more e-mobility. Hospitals need oxygen, so the by-product of the electrolysis would have a direct purpose, which may be further investigated and research on Austrian hospitals has been conducted; Beermann et al (2011). Commercial buildings may need extensive process heat. Communal buildings, or in particular schools, are empty in the Summer, so the PV on the roof can especially be used to produce hydrogen which can be stored for it’s energy consumption in Winter.

The other aspect is the human factor which is not considered in the LCA. Apart from building state-of-the-art machines, the question is whether the user can apply it rightly. Energy is wasted due to incorrect application, due to not paying attention to the value of the primary energy sources, and due to cheap fossil energy supplied in abundance.
According to Staffell (2013) two qualitative factors that influence energy performance and therefore impact the fuel cell lifecycle are “that larger houses give improved results due to a better match with the heat to power ratio of the CHP unit”, and that more savings can be achieved when heat and power services are obtained from the fuel cell simultaneously rather than separately.

Solutions for mobility could entail less private vehicles and more mass transport, which will reduce the energy requirement for transportation. Or, the next decision by a family thinking about acquiring mobility may come to an E-bike rather than a car with a combustion engine, due to limited urban space for parking, driving and cost.

7. Economic analysis

The energetic and ecological considerations are sofar satisfying to the extent that an investment decision shall be considered based on the below economic analysis. In Section 7.1 the cost and income input of the fuel cell, and related set-up, are gathered, as well as potential inflow of funds through grants and subsidies; the latter only in theory. In Section 7.2 the proposed leasing model for the system presented in the Case study, and an appropriate leasing rate calculated, to flow into the fuel cell cash flow in Section 7.3 combining the investment and the running cost. Finally Section 7.4 briefly reviews alternative financing options for other types of buildings.

7.1 Economic analysis input based on Case study

The first part reconsiders the investment, i.e. the price of the fuel cell and the system, and the second part summarises the operating cost during the lifetime of the fuel cell.

7.1.1 Investment into the fuel cell and operating costs

The economic basis of the case study is that the house in question already exists, and it does not have to be built. The devices, as described, constitute the small system, and are to be installed in the existing house. Equipment related to energy supply that will be replaced, may have a second hand- or scrap value and is considered in Section 7.1.2.

a) Investment

The total investment into the small system is EUR 240,000; plus value-added tax VAT. The following four blocks are considered that constitute the investment amount.

- The Fronius 25F costs € 30,000; while the new model by Fronius will have a different price because the electrolyser is integrated.
  A comparable price list of other cells can be found in Annex 8.

- The PV, the inverter, the heat pump, the short-term storage, the hot water storage and a heat exchanger, amount to EUR 45,000, incl. installation cost and sundries.

- In relation to hydrogen production and storage, the electrolyser, 48 gas cylinders, plus auxiliary equipment and installations shall amount to EUR 65,000, incl. work.

- Mobility consisting of an E-scooter and a hydrogen car amount to EUR 100,000.

Naturally the biggest item to save on is the 4th block with the hydrogen car which is still very expensive (a Hyundai ix-35 FCEV costs USD 100,000). Regardless of that, once hydrogen is being produced, it makes sense to consider vehicles and other devices related to a household that may consume hydrogen.

In either case, the sum of EUR 240,000, plus value-added-tax equals EUR 288,000. Figure 7.1 summarises the individual positions to illustrate.

Block	Items	Euros
I	Fuel cell: Fronius 25 F	30,000
II	PV, inverter, heat pump, short-term storage, hot water storage, heat exchanger	45,000
III	Electrolyser, hydrogen storage	65,000
IV	E- and H2-mobility	100,000
TOTAL		240,000
	plus value-added tax 20%	288,000

Figure 7.1 Investment breakdown of the residential fuel cell in the Case study *(own construction)*

The other investment is in time, effort, knowledge, experience, dedication, health and writing this thesis. These aspects are a different kind of energy that are also put in.
The energy put in to build the fuel cell shall also come out again. As it is known, energy cannot be created, only the losses can be reduced during each conversion step. The energy put into this thesis shall also come out again, with maximum efficiency.

b) Costs

There are not many cost items with regard to most types of renewable energy, particularly PV and especially when involving energy storage, except for the equipment itself that has to be amortised.

- The annual running cost according to Heinsberg (2013) cost is EUR 600.

- While the Sun is for free, there is no fuel cost, such as for oil, pellets or other stock. Strictly speaking, the hydrogen would be the fuel which is fed into the fuel cell, and the cost can be seen as that portion of the investment related to hydrogen production and storage, as well as the cost of the water inflow, needed to produce the hydrogen. However, the "fuel" cost to be considered is further up in the energy chain, i.e. at the primary energy stage, which is comparable to oil and others, while hydrogen is considered secondary energy. The source of primary "renewable" energy, the Sun, supplies the PV which supplies the electrolyser. Therefore, the investment of the PV may be considered, resp. it's annual amortisation rate. If the PV itself came at a cost of EUR 15,000, and the amortisation was calculated at 30 years, then that quotient would be weighted by the portion of annual PV yield related specifically to the hydrogen production, which at 2,500 kWh (used to electrolyse for 500 hours) of 14,600 kWh total annual PV yield equals 17%, equal to EUR 85 p.a.

- There is no electricity cost to run the 50 W of the fuel cell, as is obtained from PV.

- Waste management is based on the presumption that minimum 50% of the fuel cell (Section 6.2.2) is being recycled upon the owner returning the end-of-life fuel cell to the manufacturer, and for the remaining 50%, which may be incinerated or gone to landfill, that cost is at least the same as the purchase price of the cell, if not more. 50% of EUR 30,000 is EUR 15,000, due in Year 21 of the Cash flow in Section 7.3.

Therefore, the items to be included are EUR 600 maintenance cost and EUR 15,000 disposal/non-recyclable at the end of the lifetime.

7.1.2 Grants and subsidies (including feed-in tariff)

The below account is divided into grants, subsidies and extraordinary one-off gains.

a) Grants

Grants are always temporary, and occasionally by auction or on a first-come-basis. They should never be relied upon but are a useful like-to-have that reduce investment.

As the Case study is in Tyrol, the Tyrolian energy company (tiroler wasserkraft – TIWAG) is resorted to. They have already stopped giving out grants for e-mobility. Meanwhile they have on offer grants for heat pumps, of up to EUR 3,000 per unit which are refunded over 5 years in partial amounts, however, being deducted from the gas bill, so not paid out. Their formula is that 75% of the heat are obtained from their district heating and 25% from own heat pump. Probably, this precise model may not apply to the investment in question, and needs further research.

The State of Tyrol contributes with a long list of grants, particularly in the field of refurbishment of buildings, when renewable energy technology, such as solar, thermal improvements, heat pumps and other energy saving means are included. If the solar panel area is more than 100 m² and the total investment more than EUR 10,000, then the grant will be 30% of the eligible part of the investment. But, these grants are aimed at small- and medium-sized enterprises. It becomes relevant if the electrolyser and the fuel cell were to power an office building or a building of any other commercial nature.

Furthermore, 124 communities in Tyrol support with grants as well, solar thermal and photovoltaic, biomass, heat pumps, insulation, new windows, energy consultants and also E-mobility. Pending the precise location, this has to be checked regularly.

b) Subsidies (feed-in tariff)

TIWAG also supports the feeding-in of excess PV energy into the public grid with EUR 0.15 kWh (incl. VAT), however one is allowed to have max. 5 kW peak only, and one needs to be a client of TIWAG. In this Case study the tariff may not apply.

c) Extraordinary gains

From another perspective, there may be contributors that reduce the investment cost.

Sale of old equipment: heating, boilers etc. sold in replacement for the equipment of the hydrogen and fuel cell technology may fetch a price online or at a scrap yard.

Thanks to heat exchangers recuperating heat from various processes (showers, kitchen water, dish washing, washing machine, gardening and fuel cell heat), savings can be obtained for every kilowatt hour that does not need to be produced. This in turn helps to extend the useful lifetime of the equipment.

Tax is an important issue. Any refurbishments done to an existing building which employs ‘energy saving measures’, can, in the entirety of their amount, be deducted from the income tax; income law, LStR 2002 Rz 522 ff, Ministry of Finance, BMF.

7.2 Presenting a leasing model for the small system

In a leasing model, the consumers do not invest in the fuel cell and related equipment. Rather a pre-agreed monthly rate is paid, Hearn (2013), as shall be determined below. The leasing model consists of a depreciation fee, a financing fee and a lease charge.

The investment amount according to Section 7.1.1 is **EUR 288,000** for the system. The consumers pay one time 25% of the investment amount equal to **EUR 72,000**. Then, **EUR 1,108.80** (incl. tax) are paid **monthly**, covering the depreciation and the leasing fee for 20 years, amounting to EUR 13,305.60 p.a. Plus **annual** maintenance of **EUR 2,100** amounts to a total EUR 3,208.80 per year. Not yet included is insurance.

The service provider, leasing company or utility company, calculates a lease charge of 17% on the investment amount amounting to EUR 48,960, and is the leasing fee above. Ownership stays with the service provider, as well as the recycling activity, and possible exchange for newer technology. The contribution for waste management of EUR 15,000, due at the end of the useful lifetime, is taken care by the service provider.

Table 7.1 summarises the variables derived, and Table 7.2 shows their implementation.

Table 7.1 Determining the variables for the leasing model *(calculation based on Hearn-formulae)*

Net capitalised cost	Investment less down-payment less residual value	**EUR 216,000** = 288,000 – 43,200
Down-payment	A down-payment on total investment (25%)	**EUR 72,000** = EUR 288,000 * 25%
Residual value	It applies only if the equipment were sold after 20 years (15%)	**EUR 43,200** = EUR 288,000 * 15%
Depreciation	Net capitalised cost less residual value	**EUR 172,800** = EUR 288,000 – 115,200
Lease charge	17% of the investment amount	**EUR 48,960** = EUR 288,000 * 17%

Table 7.2 Monthly depreciation and lease fee for the small system *(own construction, based on Hearn)*

Depreciation fee	(Net capitalised cost – Residual value) Term	**EUR 720 / month** = (EUR 216,000 – EUR 43,200) 240
Money factor	Lease charge [(Net cap. cost + Resid. value) * Term]	**0.00079** = EUR 48,960 EUR 259,200 * 240
Leasing fee	(Net cap. cost + Resid. value) * Money factor; also: 'the lease charge divided by the term'	**EUR 204 / month** = EUR 259,200 * 0.00079
Lease payment	Depreciation fee + Finance fee	**EUR 924** (excl. tax) = EUR 720 + EUR 204

7.3 Fuel cell cash flow

Taking all inflows and outflows spread over the time results in the following Table 7.3. EUR 19,000 are incurred as the fee for the MSc course, which are only noted in Year 0 but do not affect the calculation. A down payment of 25% equal to EUR 72,000 is paid by the home-owner in Year 1. In Year 21 the disposal fee applies equal to EUR 15,000. The cost items are the lease payment of EUR 924 per month or EUR 11,088 per year plus the maintenance fee of EUR 600; incl. tax.

Table 7.3 Fuel cell cash flow *(own construction)*

in EUR	**Own pay**	**Deprec.**	**Leas. fee**	**Lease paym.**	**Tax**	**Gross**	**Mainten.**	**Totals**	**Discounted**	
					20%				2.5%	*2.5%*
		720/m.	204/m.	924/month	184,80/m.	1,108.8/m.				*NPV*
Year										1.025
0 *	19,000									
1	**72,000**	8,640.00	2,448.00	11,088.00	2,217.60	13,305.60		**13,305.60**	13,305.60	1
2		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	13,566.44	0.976
3		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	13,235.55	0.952
4		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	12,912.73	0.929
5		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	12,597.79	0.906
6		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	12,290.52	0.884
7		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	11,990.76	0.862
8		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	11,698.30	0.841
9		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	11,412.97	0.821
10		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	11,134.61	0.801
11		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	10,863.03	0.781
12		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	10,598.08	0.762
13		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	10,339.59	0.744
14		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	10,087.41	0.725
15		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	9,841.37	0.708
16		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	9,601.34	0.690
17		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	9,367.16	0.674
18		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	9,138.69	0.657
19		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	8,915.80	0.641
20		8,640.00	2,448.00	11,088.00	2,217.60	13,305.60	600.00	**13,905.60**	8,698.34	0.626
Year 21	15,000							**15,000.00**	9,154.06	0.610
Totals:	**106,000**	172,800	48,960	221,760	44,352	266,112	11,400	**292,512**	230,750	

7.4 Energy services companies and utility companies

In a changing world, especially with regard to the liberalisation of the energy market, utility companies face new challenges. See Annex 18. The above example demonstrates that utility companies can indeed play an important role in energy storage.

7.5 Alternative financing options

For leasing larger buildings, the term contracting has emerged in recent years, and is briefly addressed. Furthermore, a trend towards financing models involving the public has also been noted in the form of public participations. A third alternative financing method is a cooperative, which has it's rural roots in the first half of the 19th Century.

a) Contracting

It is held that contracting and leasing are financing structures related to each other.[4] Contracting is more associated with energy consultancy companies and subsidiaries of utility companies, e.g. ProContracting (IKB), while leasing companies are commonly subsidiaries of financial institutions. The contractor owns and operates the functional unit and guarantees energy delivery to the consumers. Pre-agreed monthly rates, similar to the above leasing example, are paid, or the consumers are charged on a per-use basis. Sofar this has been done with regard to biomass resp. heating. Usual tenor is 15 years. A generic equation, comparable to the above leasing equation, is provided:

Monthly payment = Energy consumption + Contracting fee

b) Public participation

From own experience, having participated in a photovoltaic project by Wien Energie, the basis is a sale-and-lease-back contract that pays a monthly rent, not compounded.[5] The consumers in this case are the investors and the owners of the PV panels or other functional unit such as the fuel cell, e.g. in an apartment block or pension home.

The utility company is in charge of the operational life of the equipment from beginning to end, feeds the produced energy into the grid, bills the customers, and pays out to the investors on annual basis a fee, similar to the rent of a car. The issue of taxation prevails, as legislation to date does not clearly stipulate the legal status of the investor earning income. The investment equation below is based on the individual.

Investment = Participation amount *(Monthly rent * Term)

c) The cooperative

The inhabitants in a given building together own the equipment resp. the fuel cell in the form of a cooperative, where each participating inhabitant is a shareholder. A calculation background is found in a project description of an energy cooperative.[6]

The focus is to divide the investment amount among several shareholders. Though it does not have to be portioned equally, small and large shareholders have equal votes.

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[4] *There are many different types of contracting offered in relation to renewable energy projects, which are also referred to as: energy leasing, photovoltaic contracting, biomass contracting, installation contracting and energy performance contracting.*

[5] *In addition, the City of Vienna is also providing support in form of a one time-grant, at 0.3% per module.*

[6] Energiegenossenschaft Starkenburg eG

Farmers, for example, collect their firewood and deliver it to a biomass plant, which they own, for a pyrolysis process to run either a gas engine that produces electricity, or to undergo a further methanisation process to produce natural gas, to distribute to homes or commercial facilities, as these so-called off-takers need a lot of process heat. If the off-takers are equipped with e.g. a solid-oxide fuel cell, or a fuel cell that caters for a reforming device to reform the methane to hydrogen, then a separate cooperative made up of stakeholders may be formed, who have a moral obligation to keep the system upright, and to maintain the equipment and support each other when necessary.

In such a set-up, the PEM fuel cell running on hydrogen from renewable sources has no place, as it will not need the natural gas. But, the electrolyser installed in a wind park may produce hydrogen which is further enriched with carbon, to form methane, which is again distributed in the grid for heating purposes, referred to as power-to-gas. By producing hydrogen, it can also be stored and serve as the fuel for an H_2-filling station. It can be owned by a cooperative, whose stakeholders wish to have a say in the plan.

Renewable energy is suitable for these models, and is exchanged and counted in kWh. According to energy architect Schulze-Darup: 'energy becomes the leading currency'.
As the shareholders are stakeholders due to being their own off-takers of what they own and produce, the issue of a commercial gain in the given structure comes in second to the energy that is being produced from renewable sources. Other than the feed-in tariff, or the fees paid by commercial facilities, at times when the plant does not generate any or little income, the cooperative members can receive their dividend in kWh of energy, instead of cash, and use this energy right away, or store it by means of
hydrogen for a later use. Or, to trade it to someone who needs energy more urgently.

8. Description of results

The purpose of this Section is to summarise in tables the core information of the proposed Case study, and to use it as an instrument for future assessment of fuel cells.

8.1 Energetic efficiency and losses

Returning to the System overview from Section 2.1.2, all figures relating to annual energy production resp. utilisation, as well as efficiencies and losses, as described in Section 4 and calculated in Section 5 can now be entered, and is seen on the next page.

Figure 8.1 shows all figures of annual energy (right side of the dotted line) resp. required capacity (left side of the dotted line) and efficiencies resp. losses at each stage.

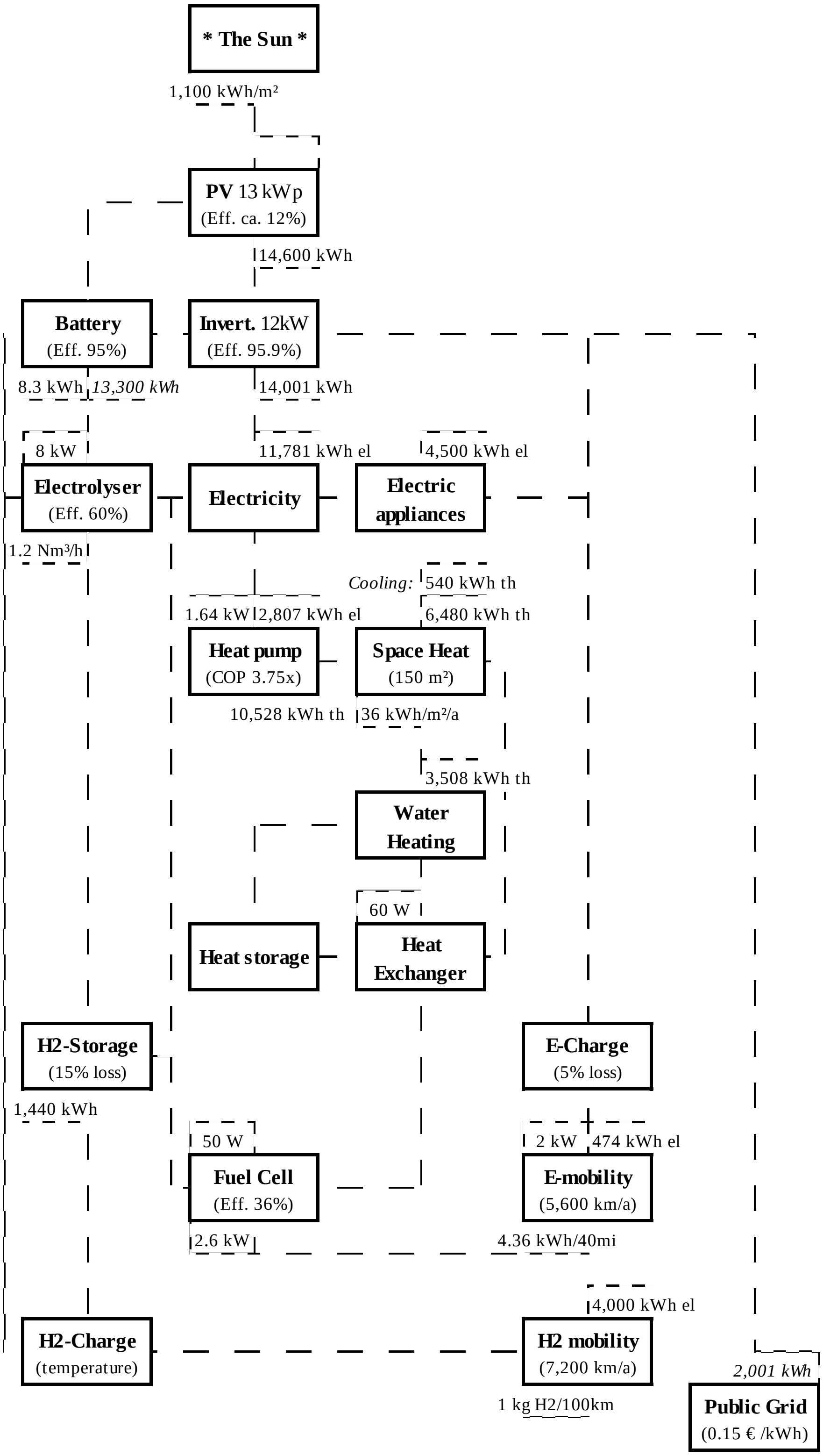


Figure 8.1 System overview with efficiencies, losses and annual energy *(Source: own construction)*

8.2 Overview of LCA results for the fuel cell

The functional unit, Fronius 25F fuel cell, runs 10,000 hours over 20 years and the maximum possible exergy is 6,550.26 MJ. It weighs 300 kg. Emissions are due to the manufacturing process of mining platinum, but most of the platinum and steel can be recycled and reused. Graphite and carbon are used for the membrane assembly area and ways have to be found to reduce their content. Figure 8.2 summarises the main issues.

Lifecycle assessment framework	
Goal and Scope Definition	**Interpretation**
a) functional unit: Fronius 25F	
b) 20 year-exergy: 6,550.26 MJ	a) expand useful lifetime
c) scope: manufacture and recycle	
Inventory analysis	
a) at operation: H2-input1,300 kg, water-output 11,200 kg	b) sustainability of sourcing water
b) at manufacture: SO2 and NOX emit in mining of platinum	
c) at end-of-life: platinum and steel are recycled and reused	c) minimum of 50% is being recycled
Impact assessment	
a) global wamring potential is given by CO2, CH4, N2O	d) investigate further about emissions
b) components using graphite and carbon contribute highest	
in consuming energy resources and causing acidification	e) to invest in research reducing carbon

Figure 8.2 LCA summary *(Source: LCA model)*

As the ecological analysis has shown, the main attention needs to be drawn in the manufacturing stage with regard to causing emissions, increasing the global warming potential and intensifying acidification. The main contributors in terms of consuming energy resources during mining and causing emissions are the graphite (from coal) and carbon, which are found in the electrodes and the bipolar plates of the fuel cell.

8.3 Economic considerations

In Section 4 the Case study was presented employing the Fronius 25F fuel cell. It costs EUR 30,000 currently, and for reasons, also dealing with environmental aspects, it is recommended that energy services companies or subsidiaries of utility companies should manage the installation, maintenance and disposal, incl. recycling, of such equipment to get a standardised approach implemented. Rather than home-owners taking the long way to learn and do troubleshooting. The leasing model, and the contracting model related to it, have already been practiced with regard to energy financing, and in the case of Japan, also with fuel cells, and should be recommended.

9. Conclusions

Four messages about hydrogen and the fuel cell are taken out of this master's thesis.

9.1 The fuel cell

A PEM fuel cell supplied with hydrogen has an efficiency of 36%, and when the photovoltaic producing the energy for the electrolyser, the storage and related equipment is factored in, then the efficiency is 18%; meaning one-fifth of the energy produced by the PV. The fuel cell is only responsible for 500 hours, or 1,000 kWh of the annual requirement of 10,528 kWh per year. Rather than improving the efficiency, the emphasis is to find different materials and streamline the manufacturing process.

9.2 The hydrogen

Hydrogen is best produced from renewable energy sources, such as the excess PV yield, as the corresponding electrolyser, with an efficiency of 60%, requires more energy to produce the hydrogen then later can be extracted from the hydrogen. Furthermore, hydrogen has to be taken with caution, and safety issues need to be observed; it is a learning process for society. In Austria the level of penetration (Annex 4) is good, and there is sufficient potential to work with this gas as a way to store renewable energy.

9.3 Annual energy demand of a single-family home

The annual heat requirement, the electricity needed for the heat pump and electric appliances as well as charging of e-mobility, and last not least the electricity needed for the electrolyser, including losses and efficiencies, amounted to 11,781 kWh p.a. Not only residential but also communal and commercial buildings will feature more E-charging stations. In the case of hospitals, the by-product oxygen has a direct purpose in the surgery. Other trends include the concept to store energy on a community-basis.

9.4 Fuel cell financing options

Financing model include leasing or contracting as well as public participations, cooperatives and other forms. The consumer pays for the energy supply and the service, while the energy services or the utility company owns and maintains the equipment.

Acknowledgements

Thank you to my Family who supported me throughout the course and writing this thesis and for their patience.

Thank you to the MSc Course at TU Vienna which has changed my outlook on life for the better, most strongly with regard to renewable energy, efficiency and storage, as well as many individuals, lecturers and students, entered into dialogues with.

Thank you to various companies and persons, foremost Fronius, met, spoken to and exchanged ideas in the last 8 eight years, during exhibitions, conferences and seminars, and for a lot of good advice received.

As a closing thought the below picture of an electricity generation plant is submitted. It was owned and operated in the 1920s and 30s by my Great-grandfather Berthold Schulz (1879-1950) in Hanerau-Hademarschen. He was said to have stored excess energy in glass-walled accumulators filled with acidic solutions, and glass rods sticking out.

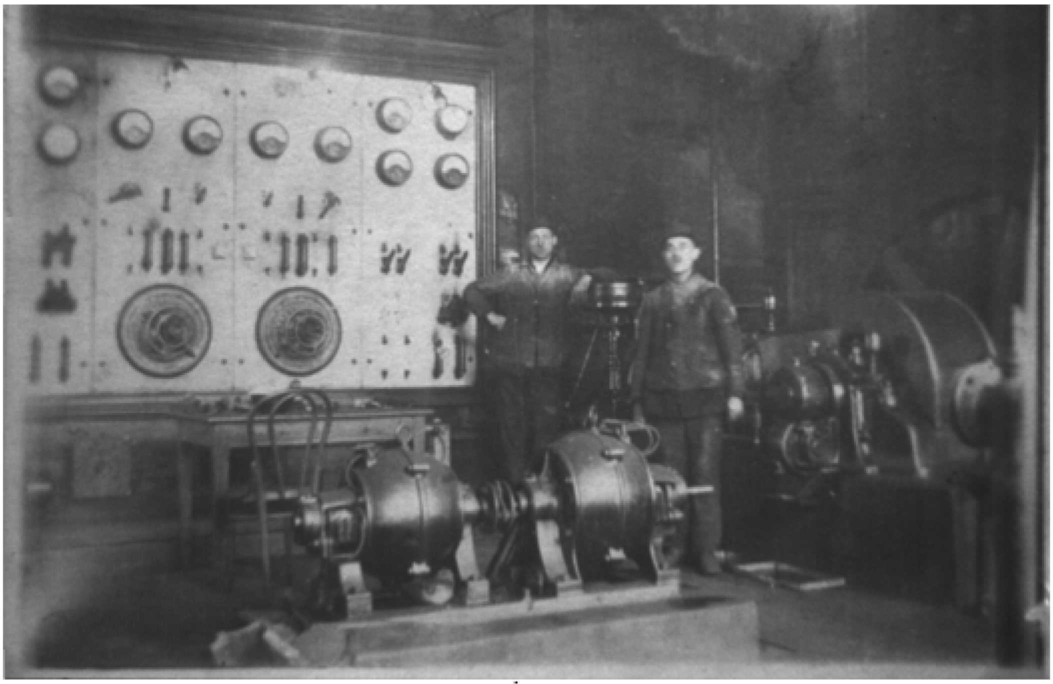


Figure 9.1 Electricity generation in the early 20th Century *Source: Wikipedia "Hanerau-Hademarschen" (2013)*

References

Aachen; Safety and Security Assessment, "Roads2HyCom"; Aachen University, Institut für Kraftfahrzeuge; http://www.ika.rwth-aachen.de/r2h/index.php/Safety_and_Security_Assessment, August 2013.

AEE Intec, „Solar-supported heating networks in multi-storey residential buildings – A planning handbook with a holistic approach"; 1st edition 2004, Gleisdorf.

Aichele, G., Freiburg, 2004; "Der Graf und der Wasserstoff"; http://www.dvs-aft.de/M/0/Tew/Sew/19X/04.pdf, 8/*13*.

Ajanovic (2008), A.; On the economics of hydrogen from renewable energy sources as an alternative fuel in transport sector in Austria, International Journal of Hydrogen Energy 33 (2008) 4223-4234; Elsevier, Amsterdam.

Ajanovic (2012), A; Lecture Module 9: "Scenarios for future technologies: hydrogen from renewable energy sources (RES) - Photovoltaics, wind, hydro power, biomass", held on 07.12.12, Vienna University of Technology, Energy Economics Group (EEG), Institute of Energy Systems and Electric Drives.

Augsburg; Fachhochschule Augsburg; Educational material; „Praktikumsanleitung, Brennstoffzelle"; Sep. 2004.

„**Bacon**"; The Corrosion Doctors, on Francis T. Bacon; http://www.corrosion-doctors.org/Biographies/BaconBio.htm, *August 2013*.

Baker, R. & **Zhang**, J.; Proton Exchange Membrane or Polymer Electrolyte Membrane (PEM) Fuel Cells, April 2011; Institute or Fuel Cell Innovation, National Research Council of Canada, Vancouver; appearing in Electrochemistry Encyclopedia.

Baufumé, S., et al; Article: "GIS-based scenario calculations for a nationwide German hydrogen pipeline infrastructure", Forschungszentrum Jülich GmbH, Institute of Energy and Climate Research – Systems Analysis and Technology Evaluation (IEK-STE), in International Journal of Hydrogen Energy 38 (2013) 3813 – 3829.

Beermann, M., **et al**; „Die Öko-Wasserstoff-Tankstelle der Zukunft", Demonstration der gekoppelten elektrolytischen Erzeugung und Nutzung von Wasserstoff, Sauerstoff und Wärme aus Öko-Strom am HyCentA, April 2011; Joanneum Research, Resources Institut für Wasser, Energie und Nachhaltigkeit, Graz.

"**BMWFJ, 2012**", Ministry of Economy; **Energieeffizienz: Die Entwicklung des Bereichs ‚Energieeffizienz' in der Europäischen Union**; Chapter 4, July 2012; http://www.bmwfj.gv.at/EnergieUndBergbau/Energieeffizienz/Documents/Energieeffizienz%20-%20Die%20Entwickung%20der%20Energieeffizienz%20in%20der%20EU%20-%20Inhaltsverzeichnis.pdf, 2/*13*.

Boetius, H.; **Die Wasserstoffwende, Eine neue Form der Energieversorgung**; dtv, Munich, 2005.

BOKU; University of Natural Resources and Applied Life Sciences (BOKU), Vienna in **Die Presse**-online Klimawandel: Tirol droht eine "Heißzeit", 29.07.2008.

Boustead Consulting Ltd., "LCAs in the modern world"; http://www.boustead-consulting.co.uk/iso14040.htm, 8/13.

Brinner, A. and Hug, W.; Dezentrale Herstellung von Wasserstoff durch Elektrolyse, 2002; Institut für Fahrzeugkonzepte des Deut. Zentrums f. Luft- und Raumfahrt e.V. (DLR), Stuttgart.

"**CFCL, BlueGen**"; Die BHKW-Infothek, "Ceramic Fuel Cells: BlueGen"; http://www.bhkw-infothek.de/bhkw-anbieter-und-hersteller/nano-bhkw-ubersicht/cfcl-bluegen/, *October 2013*.

Chemistry in Context; American Chemical Society; Wm C Brown Publ., Dubuque Iowa, 2nd ed., A project of the American Chemical Society, ed: A. Truman Schwartz et al., 1997, Chapter 5 "The Wonder of Water"; http://witcombe.sbc.edu/water/chemistrystructure.html, July 2013

Cleveland, C, ed. Lawrence T.; **Grubb, Willard Thomas**; published on September 10, 2013, retrieved from: **The Encyclopedia of Earth**, http://www.eoearth.org/view/article/153164/, *August 2013*.

Darling; The Encyclopedia of Science, **The Worlds of David Darling**; http://www.daviddarling.info/encyclopedia/H/hydrogen.html, August 2013.

Dobler, H.-D. and Fischer, U. et al; **Fachkunde Metall, Mechanische Technologie**, 54th edition; Verlag Europa-Lehrmittel, Haan-Gruiten, 2003.

„**DWV**“; German Hydrogen and Fuel Cell Association; “Wasserstoff. Der neue Eenergieträger. Eine fachliche Einführung vom Deutschen Wasserstoff- und Brennstoffzellen-Verband e.V. – DWV“; Berlin, 2009.
– > Hydrogen production methods: statistics originating to data from 2004,more recent data could not be found.

„**EC-FP5**“; European Commission, Fifth Framework Programme (1998-2002); http://ec.europa.eu/research/energy/pdf/12_hystorypart2_en.pdf, February 2013.

Ecowatt erneuerbare energien gmbh; „Hausversorgung auf Basis einer Brennstoffzelle“, May 2007; http://www.noest.or.at/intern/dokumente/209_Endbericht_Hausenergie_Brennstoffzelle.pdf, July 2013.

“Ene.field”, **Riddoch**, F.; Presentation: „Ene.field, European wide-field trials for residential fuel cell micro-CHP (303462)”, 2012; COGEN Europe, The European Association for the Promotion of Cogeneration, Brussels.
“**ene-field**”; European Union, Seventh Framework Programme, ene.field; Fuel Cells and Hydrogen Joint Technology Initiative, http://enefield.eu/introduction/, February 2013.

enerChange GmbH, Innsbruck; Systembausteine; http://www.enerchange.net/?Infrastruktur, September 2013.

Energiegenossenschaft Starkenburg eG; Projekt “WindSTARK 1”; **Bau einer Windkraftanlage in Ober-Beerbach („Neutscher Höhe“)**, Projektbeschreibung der Energiegenossenschaft Starkenburg eG; http://www.energiegenossenschaft-starkenburg.de/unterlagen/informationen/projektbeschreibung_windstark_1.pdf, August 2013.

“**Epsom**”; Epsom and Ewell History Explorer, on “C.F. Schönbein”; http://www.epsomandewellhistoryexplorer.org.uk/Schonbein.html; *August 2013*

“**EUVPP**”; European Virtual Fuel Cell Power Plant (NNE5-2000-2008); http://ec.europa.eu/energy/efficiency/industry/doc/euvpp.pdf, February 2013.

Fechner, H. and **Weiss**, W.; Course Script “Module 3 – Solar Energy – Solar Heating & Photovoltaics”, April 19-21 2012; TU Wien, Vienna.

Fronius International GmbH, “The house of the future”; https://www.fronius.com/cps/rde/xchg/SID-2C109694-087DBF3D/fronius_international/hs.xsl/83_25821_ENG_HTML.htm, May 2013.
Fronius International GmbH; discussions on 19.6.13 (Munich), 2.9.13 (Wels) and 19.11.13 (St. Pölten)
Video-stream “Günter Fronius, der Gründer im Interview”, **Fronius International GmbH**, 2 Oct 2012; http://www.youtube.com/watch?v=QT0pO_AWhns&list=UU4R-vRhbUlgtKFgDaKwAJfw
Inverter: IG Plus 150 V-3; http://www.fronius.com/cps/rde/xchg/SID-4BDDD710-BC09AA69/fronius_international/hs.xsl/83_10597_ENG_HTML.htm , May 2013.
Central Inverter: CL 48.0; http://www.fronius.com/cps/rde/xchg/SID-43888E43-D422B9C3/fronius_international/hs.xsl/83_17800_ENG_HTML.htm, May 2013.

FuelCell Today; History; http://www.fuelcelltoday.com/about-fuel-cells/history#The 1980s, 2012.

FuelCells; Fuel Cells 2000; “Benefits”; www.fuelcells.org, September 2013.

“**Gappmaier, 2012**”, Ing. Dennis Gappmaier; **Kennzahlen des Energieausweises**; http://www.salzburg.gv.at/121129_geq_gappmaier_praesentation_renexpo_20121127ab.pdf, *February 2013*.

Geitmann, S.; **Energiewende 3.0, Mit Wasserstoff und Brennstoffzellen**; Hydrogeit Verlag, Oberkrämer, 2012.
Geitmann, S.; **Wasserstoffautos, Was uns in Zukunft bewegt**; Hydrogeit, Kremmen, 2006.

Grot; personal website of Walther G. Grot, inventor of membrane NAFION™; http://www.nafion.mysite.com/, *9/13*.

Grove, W.; XXIV. “On Voltaic Series and the Combination of Gases by Platinum.”, Swansea, Dec. 14, 1838; in The London and Edinburgh Philosophical Magazine and Journal of Science., Vol. XIV, January-June 1839, Taylor, London, pp. 127-130.
Grove, W.; LXXII. “On a Gaseous Voltaic Battery.”, London Institution, Oct. 29, 1842; in The London and Edinburgh Philosophical Magazine and Journal of Science., Vol. XXI, July-December 1842, Taylor, London, pp. 417-420;
found in “Historic Publications in Electrochemistry”, Electrochemical Science and Technology Information Resource (ESTIR), http://electrochem.cwru.edu/estir/history.htm

Haas, R. **et al**; The Changing Structure of the Electric Utility Industry in Europe: Liberalisation, New Demands and Remaining Barriers, 2009, in Bausch, A., Schwenker, B. (eds.), **Handbook Utility Management**; Springer.

Hearn, A.; LeaseGuide.com; "Car Lease Payment Formula"; http://www.leaseguide.com/lease08.htm, *August 2013*.

Heinsberg; website of the city of Heinsberg, producing the BlueGen-model FC for CFCL; http://www.brennstoffzelle-heinsberg.de/, July 2013.

Heinzel, A., **Mahlendorf**, F. and **Roes**, J.; **Brennstoffzellen**, Chapter: „1 Brennstoffzellen – Ein Überblick", 2006; C.F. Müller Verlag, Heidelberg.

Histalp (ZAMG) Histalp Management, Department of Climate Research; Hist. Instr. Climat. Surface Time Series oft he Greater Alpine Region; http://www.zamg.ac.at/histalp/images/stationmode/T01_INF_year.png, June 2013.

„**HLK**"; „Heizung Lüftung Klimatechnik"; monthly, WEKA Verlag, Vienna.

„**HZwei**"; "HZwei, Das Magazin für Wasserstoff und Brennstoffzellen"; quarterly, Hydrogeit Verlag, Oberkrämer.

Hyundai; Article; http://www.autocar.co.uk/car-review/hyundai/ix35/first-drives/hyundai-ix35-fuel-cell-first-drive-review, May 2013.

IDM Energiesysteme GmbH; Heat pump:
Terra IL; http://www.idm-energie.at/de/luftwaermepumpen-terra-il.html, June 2013
Terra AL; http://www.idm-energie.at/de/luftwaermepumpe-terra-al-twin.html

IEA/OECD, Report: "IEA Energy Technology Essentials, ETE 05, Hydrogen Production & Distribution", April 2007; www.iea.org/techno/essentials.asp.
IEA/OECD, Report: "IEA Energy Technology Essentials, ETE 06, Fuel Cells", April 2007; www.iea.org/techno/essentials.asp.

„**IEWT 2005**"; Internationale Energiewirtschaftstagung; „50 Monate Betriebserfahrung der ARGE Brennstoffzelle mit SOFC-und PEM-Brennstoffzellen-Heizgeräten" (Energie AG); http://www.energieag.at/eag_at/resources/257501226587649392_326145711647059423_n$5lgFAT.pdf, Feb. 2013.

Innsbruck, City Council, Stadt Innsbruck; "Feinstaub: Kampf ohne Tabu", Periodical: Mein Bezirk; http://www.meinbezirk.at/innsbruck/politik/feinstaub-kampf-ohne-tabu-d129566.html, July 2013.
Innsbruck, Environment Council, Stadt Innsbruck, Umweltreferat, Innsbrucker Energieentwicklungsplan; Abschlussbericht der Phase I (08.2009 bis 12. 2010), March 2011.
Innsbruck statistics, Stadt Innsbruck, Statistik und Berichtswesen; Monats- und Jahrestemperaturmittel seit 1906; http://www.innsbruck.gv.at/page.cfm?vpath=verwaltung/statistiken--zahlen/klima, July 2013.

Kronberger, H.; **Geht uns aus der Sonne, Die Zukunft hat begonnen**: Uranus Verlagsges.m.b.H., Wien, 2011.

KTM-Sportmotorcycle AG; "KTM E-Speed Electric Scooter Concept Revealed in Tokyo", Motorcycle-blog; http://blog.motorcycle.com/2013/03/22/manufacturers/ktm/ktm-e-speed-electric-scooter-concept-revealed-in-tokyo/, June 2013.

Kurzweil, P.; **Brennstoffzellentechnik**, Chapter: „2 Thermodynamik und Kinetik der Brennstoffzelle", 2013; Springer Fachmedien, Wiesbaden.

Larminie, J. and Dicks, A.; **Fuel Cell Systems Explained**; Oxford Brookes University, Wiley, Chichester, 2003.

Lin, B.; **Hydrogen fuel cell scooters for urban Asia** (Master's Thesis); Princeton University, Princeton, 1999.

Linde Gas Austria 2008; "Rechnen Sie mit Wasserstoff. Die Datentabelle.", 07.05.2008; LINDE GAS GmbH, Anwendungstechnisches Zentrum, Vienna.

Masoni, P. et al; FC-Hy Guide, Guidance Document for performing LCAs on Fuel Cells and H_2 Technologies, 30.9.2011; Fuel Cells and Hydrogen – Joint Undertaking, Brussels.

Meyers; Meyers Großes Konversations-Lexikon. 6th ed., 1st Vol., „A bis Astigmatismus", Leipzig and Vienna, Bibliographic Institute, 1903.

Milics, G. and **Neményi**, M.; **Renewable Energy Textbooks, Geothermal Energy Resources: Thermodynamics and Utilization, Volume 3**; University of West Hungary, Faculty of Agricultural and Food Sciences, Institute of Biosystems Engineering, Monocopy Bt., Mosonmagyaróvár, 2008

Mining Intelligence Database, "Platinum Mining in South Africa"; http://www.projectsiq.co.za/platinum-mining-in-south-africa.htm, *September 2013*.

Nakicenovic/Haas (2010); Haas., R., Lecture Module 1: "Introduction to energy systems and the relevance of renewables", held on 17.10.11, Vienna University of Technology, Energy Economics Group (EEG), Institute of Energy Systems and Electric Drives,
and diagram in **Haas**, R. and **Nakicenovic**, N. et al; Towards sustainability of energy systems: A primer on how to apply the concept of energy services to identify necessary trends and policies; in Elsevier, Amsterdam, Energy Policy 36 (2008) 4012-4021, p. 4013.

Najjar, Y.; Review, Hydrogen safety: The road toward green technology, 5 July 2013; in International Journal of Hydrogen Energy 38 (2013) 10716–10728.

Nave, R.; Georgia State University, Department of Physics & Astronomy; http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/electrol.html, July 2013; data from **Schroeder**, Daniel V., An Introduction to Thermal Physics, Addison-Wesley, 2000.

Nogueda, D; Life Cycle Assessment of PET Bottle Recycling: A Case Study for Mexico, 03.06.2013; TU Vienna, MSc Environmental Technology & International Affairs,
and quotation in Guinée et al; **M.A.J. Handbook on life cycle assessment. Operational guide to the ISO standards**; Kluwer Academic Publishers, Dordrecht, 2002.

Obersteiner, C; Course Script of Module 1, Lecture on "Market integration of renewables and storages", 2011.

Ohl, M.; Script: „Hauptfach- und APMB-Versuch, Elektrolyse und Brennstoffzelle"; Universität Stuttgart, Institut für Energiewirtschaft und Rationelle Energieanwendung.

Ostwald, F.; "Die wissenschaftliche Elektrochemie der Gegenwart und die technische der Zukunft.", in Zeitschrift für Elektrotechnik und Elektrochemie. 1894-95. Knapp, Halle, p. 122-125; *found in "Historic Publications in Electrochemistry", Electrochemical Science and Technology Information Resource (ESTIR), http://electrochem.cwru.edu/estir/history.htm*

Panasonic; "Launch of New 'Ene-Farm' Home Fuel Cell Product More Affordable and Easier to Install"; http://panasonic.co.jp/corp/news/official.data/data.dir/2013/01/en130117-5/en130117-5.html, *June 2013*.

Pehnt, M.; Life-cycle assessment of fuel cell stacks; German Aerospace Center (DLR), Institute for Technical Thermodynamics, System Analysis and Technology Assessment; Int. Jour. of Hydrogen Energy 26 (2001) 91-101.

„**Pike Research 2011**"; Fuel Cells in Asia Pacific (3Q 2011); in http://www.navigantresearch.com/wordpress/wp-content/uploads/2011/09/FCAP-11-Executive-Summary.pdf, May 2013.
"**Pike 2012**"; Residential Combined Heat and Power (1Q2012); in http://www.navigantresearch.com/wordpress/wp-content/uploads/2012/02/RCHP-12-Executive-Summary.pdf, May 2013.

PRWeb, Glob. Fluorspar Market to Reach 5.94 Mill. M.Tons by 2017, Acc. to New Report by Global Ind. Analysts, Inc., 23.2.12; http://www.prweb.com/releases/fluorspar_fluorite/fluorocarbons/prweb9221596.htm, 10/13.

PVGIS, Ispra *(Online-PV calculation tool)*; EU Joint Research Centre; Photovoltaic Geographical Information System; http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php, Summer 2013.

„**Rutgers**"; Presentation: "Describing a fuel cell's performance and efficiency"; Edward J. Bloustein School of Planning and Public Policy, Hydrogen Learning Center;
in http://policy.rutgers.edu/ceeep/hydrogen/education/ThermodynamicsFuelCells.pdf, June 2013.

Schönbein, C.; X. "On the Voltaic Polarization of certain Solid and Fluid Substances.", Bâle, Dec. 1838; in The London and Edinburgh Philosophical Magazine and Journal of Science., Vol. XIV, January-June 1839, Taylor, London, pp. 43-45; *found in "Historic Publications in Electrochemistry", Electrochemical Science and Technology Information Resource (ESTIR), http://electrochem.cwru.edu/estir/history.htm*

Simader, G. et al, Austrian Energy Agency; Report: "Hydrogen and Fuel Cell RTD in Austria: Country Picture, Report in the frame of HYSOCIETY project", July 2004.

Schwaiger, R.; Lecture Module 2: "General introduction on environmental challenges for bioenergy, II. Life cycle assessment (LCA), pp.28-99", held on 03.3.12, Joanneum Research, Graz.

Smartfox, DAfi GmbH; Smart metre and heating rod; http://www.smartfox.at/Setangebote/ http://smartfox.at/cmssystem/images/bilder/Installations_Betriebsanleitung%20SMARTFOX%209v0.pdf, 7/2013.

Smolinka, T., Günther, M. and Garche, J.; NOW-Studie, "Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien", Kurzfassung des Abschlussberichts on5.7.2011; Fraunhofer ISE and FCBAT.

Sørensen, B.; Total life-cycle assessment of PEM fuel cell car, 2005; Roskilde University , Energy & Environment Group.
Sørensen, B.; **Life-Cycle Analysis of Energy Systems, From Methodology to Applications**; RSC, Cambridge, 2011.

Staffell, I. **et al**; (1) Energy and carbon payback times for solid oxide fuel cell based domestic CHP, 2012; University of Birmingham, Department of Chemical Engineering, Edgbaston.
Staffell, I. and **Ingram**, A.; Life cycle assessment of an alkaline fuel cell CHP system, 8 February 2010; University of Birmingham, Edgbaston.
Staffell, I. and **Green**, R.; The cost of domestic fuel cell micro-CHP systems; Imperial College Business School, London, 27 November 2012; in International Journal of Hydrogen Energy 38 (2013) 1088–1102.

State of Tyrol, grants; http://www.tirol.gv.at/foerderungen/, October 2013.

Statistik Austria; Statistisches Jahrbuch Österreichs; https://www.statistik.at/web_de/services/stat_jahrbuch/index.html, August 2013

Steele, B. & **Heinzel**, A.; Article: "Materials for fuel-cell technologies", in www.nature.com, Vol. 414, 15 November 2001, Macmillan Magazines Ltd., pp. 345-352.

Stolten, D. et al, Presentation: An Overview on Electrolysis on October 26-28, 2010, WICaC 2010 at Campinas, Brasil; Institute for Fuel Cells, Juelich Research Center, Germany.

Sunlight Electric, LLC; 160 Years of Photovoltaic Technology; http://www.sunlightelectric.com/pvhistory.php, 7/13.

Sunplugged GmbH; http://sunplugged.at/mobile-photovoltaics/helis/, July 2013.

SUN-SYSTEMS GmbH; Buffer storage: Trivalent; http://www.sun-systems.at/page.php?pid=33, August 2013.

TIWAG - Tiroler Wasserkraft AG; „Energie intelligent nutzen"; http://www.tiroler-wasserkraft.at/de/hn/energieberatung/beratung_tipps/haushaltsgeraete/stromverbrauch/index.php, August 2013.

„**TU Wien, Opitz**", Dr. Alexander Opitz, Vienna University of Technology; „Chemiker entschlüsselt Reaktionen in der Brennstoffzelle", November 2007; in http://www.tuwien.ac.at/aktuelles/news_detail/article/7254/, *August 2013*.

Tyrol statistics; Amt der Tiroler Landesregiuerung, Gruppe Bau und Technik, Abteilung Wasserwirtschaft, Hydrologische Übersicht, Jahr 2012; http://www.tirol.gv.at/fileadmin/www.tirol.gv.at/themen/umwelt/wasserkreislauf/downloads/hueb2012.pdf, 7/2013.

"**Uni Münster**"; "4 BZ: Brennstoffzelle"; Westfälische Wilhelms-Universität Münster, Münster; in http://www.uni-muenster.de/imperia/md/content/physikalische_chemie/praktikum/skript_bz.pdf.

Ulsan Technopark; Ulsan Builds the World's Largest Hydrogen Town; http://www.investkorea.org/ikwork/reg/eng/ne/index.jsp?l_unit=90202&m_unit=90309&code=14501&no=608300004&bno=306270023&seq=289, June 2013.

van Rooijen, J; Report: A Life Cycle Assessment of the PureCell™ Stationery Fuel Cell System: Providing a Guide for Environmental Improvement, No. CSS06-09, June 30, 2006; University of Michigan, Center for Sustainable Systems, Ann Arbor.

Varta; Varta Storage GmbH, Battery: Engion; http://www.varta-storage.com/en/facts-specs.html, June 2013.

Walkowiak, C. and Müller, M.; Presentation: „Wasserstofftechnik und Brennstoffzellen – Proton Exchange Membrane Fuel Cell (PEMFC)" on 17.6.2005, Mechatronik, FH Darmstadt.

Wilkinson, D.; Article: "Fuel Cells", in The Electrochemical Society *Interface*, Spring 2001.

“ZSW” Kabza, A and **Jörissen**, L.; Presentation. “Die Brennstoffzelle: Energiequelle der Zukunft?”, 30.05.2001; Zentrum für Sonnenenergie- und Wasserstoffforschung, GB3: Elektrochemische Energiewandlung und –speicherung, Abteilung ECW: Elektrochemische Wasserstofftechnik, Ulm.

Annex 1: Hydrogen conversion charts

Wasserstoff-Daten

unterer Heizwert	3,00 kWh/Nm³	10,8 MJ/Nm³
	2,359 kWh/l LH_2	8,495 MJ/l LH_2
	33,33 kWh/kg	120,0 MJ/kg
oberer Heizwert	3,54 kWh/Nm³	12,75 MJ/Nm³
	2,790 kWh/l LH_2	10,04 MJ/l LH_2
	39,41 kWh/kg	141,86 MJ/kg
Dichte	0,0899 kg/Nm³	70,79 kg/m³ LH_2
Siedepunkt	20,390 K (0,1013 MPa)	
unterer Wobbe-Index	11,361 kWh/Nm³	40,898 MJ/Nm³
oberer Wobbe-Index	13,428 kWh/Nm³	48,340 MJ/Nm³
spezifische Wärmekapazität	c_p = 14,199 J/kg/K	c_v = 10,074 J/kg/K
Explosionsgrenze in Luft		4,0 – 75,0 Vol.-%
Detonationsgrenze in Luft		18,3 – 59,0 Vol.-%
Diffusionskoeffizient	0,61 cm²/s	

Der Energiegehalt von 1 Nm³ Wasserstoff entspricht 0,34 l Benzin, 1 l flüssiger Wasserstoff entspricht 0,27 l Benzin, 1 kg Wasserstoff entspricht 2,75 kg Benzin.

Gas-Umrechnungstabelle (m³ bei 15° C und 1 bar)

Gas*	kj/kg °C	m³ 15° C 1 bar	Liter flüssig 1,013 bar	kg
H_2		1	1,188	0,0841
	454,3	0,842	1	0,0708
	-252,8	11,891	14,126	1

Kompressionsfaktor (273,15 K)

Druck (MPa)	0,1013	5	10	15	20
Kompressionsfaktor	1	1,032	1,065	1,098	1,132
Druck (MPa)	25	30	35	40	50
Kompressionsfaktor	1,166	1,201	1,236	1,272	1,344
Druck (MPa)	60	70	80	90	100
Kompressionsfaktor	1,416	1,489	1,560	1,632	1,702

Daten zu Energieträgern

Wasserstoff	3,00 kWh/Nm³	33,33 kWh/kg
Rohöl	≈ 1 toe/t	≈ 11,6 kWh/kg
Diesel	≈ 10 kWh/l	≈ 11,9 kWh/kg
Benzin	≈ 8,8 kWh/l	≈ 12,0 kWh/kg
Methanol	4,44 kWh/l	5,47 kWh/kg
Methan	9,97 kWh/Nm³	13,9 kWh/kg
Erdgas (82 – 93 % CH_4)	8,8 – 10,4 kWh/Nm³	10,6 – 3,1 kWh/kg
Propan	25,89 kWh/Nm³	12,88 kWh/kg
Buthan	34,39 kWh/Nm³	12,7 kWh/kg
Stadtgas**	4,54 kWh/Nm³	7,57 kWh/kg

LH_2: 100 % para-Wasserstoff
Normbedingungen: 273,15 K; 0,1013 MPa

* Verdampfungswärme und Siedetemperatur bei 1,013 bar.
** (51 $\%_{vol}$ H_2; 18 $\%_{vol}$ Co; 19 $\%_{vol}$ CH_4; 2 $\%_{vol}$ C_nH_m; 4 $\%_{vol}$ CO_2; 6 $\%_{vol}$ N_2)
Alle Angaben ohne Gewähr.

Source: Linde Gas Austria (2008)

Annex 2: Currencies and exchange rates

EUR / €	Euro-currency
JPY	Japanese Yen
USD	United States-Dollars

Währungspaare	Letzter	Diff.%
EUR/CHF	1,2342 CHF	-0,09%
EUR/GBP	0,8459 GBP	-0,00%
EUR/USD	1,3562 USD	+0,30%
EUR/JPY	133,4760 JPY	+0,16%

Source: Raiffeisen Centrobank AG, www.rcb.at, (on 16 October 2013)

Annex 3: Additional history of the fuel cell and hydrogen

In Meyers encyclopaedia of 1903 an entry on accumulators defines them as 'collectors (Sammler), a wooden or glass box containing alternating plates, the positive ones being coated with lead oxide and the negative with a porous lead coating, to be engulfed with diluted sulphuric acid, and connected by wires of lead; either in sequence or parallel. The sulphuric acid (reduction) splits into hydrogen and sulphate, the latter flowing to the lead oxide to form lead sulphate, the oxygen joining the hydrogen to form H_2O':

$$\mathbf{PbO_2 + H_2 + H_2SO_4 = PbSO_4 + 2\ H_2O} \qquad (20)$$

According to Meyers 'such accumulators were used in electrical trains (tram) to store excess energy when it received an over-supply resp. replenish deficient energy, to bridge the fluctuating power supply, and support the dynamo engine'.

This operation was reversible, energy flowing in, energy flowing out, and could be repeated as often as until there was sulphate left. Hydrogen was used as secondary energy carrier.

The author's Great-grandfather Berthold Schulz (1879-1950) stored energy in similar fashion, as recollected by my Father, having seen glass troughs, and tubes tugged in, in the attic. Berthold Schulz operated an electricity generating-gas plant as of 1921 in Hanerau-Hademarschen. After an explosion in 1926 it was replaced by a diesel generator. Excess energy was stored in glass batteries, or accumulators.

Annex 4: Fuel cell activity in Austria

Renewable energy technology made in Austria with regard to hydropower is over 100 years old, with regard to solar thermal and geothermal pioneer work 30 resp. 70 years. Also biomass and biogas plants are not a new concept. Still, doubt exists concerning the new movement of large scale-wind, -PV, and communication and information exchange is essential. On the educational side, schooling on all levels provides for awareness. Particularly, TU Vienna and TU Graz give hydrogen and fuel cell lectures. Research centres as alpS, Innsbruck, and Joanneum Research, Graz focus on fuel cells.

The Ministry of Environment held a symposium on 24 January 2013 during which a.o. DI Martin Beermann presented about hydrogen generation from renewable sources. The Austrian Energy Agency (then called the E.V.A.) published a report in 2004 listing more than 35 projects related to hydrogen and fuel cells going on in Austria. One was the “Fuel cell heating systems for residential applications (PEFC)” in Styria, and examples were presented in Section 2.2. Two similar projects were conducted in Vienna and Upper Austria; Simader (2004). Next to Fronius and AVL List, a manufacturer of components for SOFC located in Reutte.

On 18.2.2010 DI Alexander Sautner of Salzburg-based company Masterguard Chloride (meanwhile under a different name) demonstrated a fuel cell using methanol as fuel, with small PV to run the fuel cell.

For transportation, OMV built an H_2-station in Floridsdorf in 2012, next to the HyCentA-station in Graz. Another H_2-station is planned in Bozen (proximity to Innsbruck), which already has the hydrogen buses.

Magna Steyr constructed a flat tank for fuel cell cars (Figure A4.1) used in the BMW Hydrogen 7. It can take up to 4.5 kg (at 0.4 MPa, or 4 bar) of liquid hydrogen (LH_2); HZwei (2008).

Figure A4.1 Hydrogen tank for BMW Hydrogen 7 *Source: HZwei (07/08)*

Installation companies specifically are key to the equation because they refurbish buildings and install new technology. Discussions with raymann, kraft der sonne® Photovoltaik GmbH led to the additional awareness of the Fronius Energy Cell, with subsequent introduction to responsible persons at the company in January 2013.

Through personal discussions at large, the degree of acceptance about hydrogen topics and fuel cell technology were individually tested, and may be summarised as follows:

- upon hearing the word “hydrogen”, the Hindenburg disaster sprang to the mind.
- When asked about the “fuel cell”, then all of a sudden came an enthusiastic reaction.
- Citing ‘excess energy storage with hydrogen’, curiosity arose and a dialogue began.

Annex 5: Additional research material on the membrane and corrosion

In 2007, Dr. Alexander Opitz from TU Vienna, Institute of Chemical Technologies and Analytics showed that platinum, in an SOFC, was refined in its nanostructure to increase effectiveness (see upper left hand corner in Figure A5.1). It is placed on the zirconium dioxide electrolyte. The key is that the oxygen ions leave the cathode in a more structured way, leading to the desirable consequence that more O_2-molecules were split into oxygen ions to form bonds with hydrogen, resulting in more electricity.

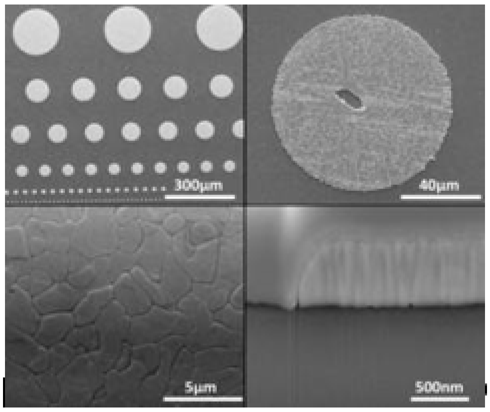


Figure A3.1 A microscopic look at the platinum electrode *Source: TU Wien, Opitz (2007)*

In January 2013, according to a HZwei-article, Shouheng Sun, a chemist at and his students at Brown University, Providence have replaced platinum with cobalt and cobalt oxide-particles (Co_3O_4), mounted on the graphite, that can catalyse the oxygen reduction in the same way, but is said to last longer, as it is more stable than platinum.

A HZwei-article on corrosion appearing in April 2013, written by researchers at Fraunhofer, stresses the temperature differences fuel cells are exposed to (-40 to 80°C), moisture from gases, resulting water resp. steam, acids and current. Hydrogen may bond with nitrogen from the air to HNO_3, or with fluorine HF, or a ‘gas-crossover’ H_2O_2 may occur, while the pH-value may drop to 4 and below as fluorine-content increases with age of the cell. Elements, such as Na, Si, Al, Mn, Fe, Ni and Ba were all traced back to the atmosphere. These are challenges to be taken seriously.

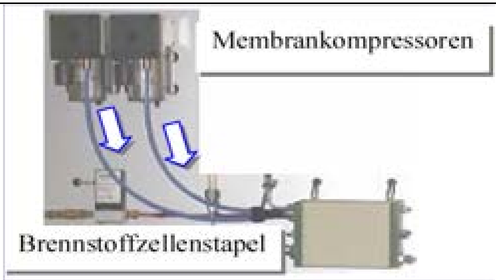
Annex 6: Bipolar plates seals

Table A6.1 Various seals with prices *Source: HZwei (07/09)*

Dichtungsmaterial	NT-PEM	DMFC	HT-PEM	max. Temperatur	Preis pro kg	Bemerkungen
Thermoplastisches Elastomer	+	-	-	80 °C	4 - 5 €	Ausgangsbasis: Kunststoff, Verarbeitung: vollautomatisch
EPDM	+	+	-	120 °C	2 €	„Gummi": guter Druckver-formungsrest, mannhafte Fertigung
Liquid Silicone Rubber (LSR)	+	-	-	180 °C	10 €	Silicon: gute Verarbeitung, gute Fließeigenschaft
Fluorkautschuk	-	+	+	220 °C	30 €	aufwendige Verarbeitung, säurebeständig, methanolb

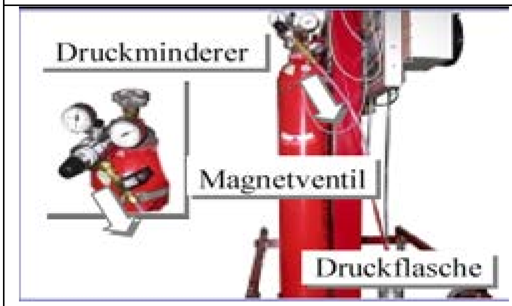
Annex 7: Related equipment of the fuel cell

Auxiliary equipment of a PEM fuel cell is illustrated and summarised in Figure A7.1 based on an educational model kit by Heliocentris, specialist in fuel cells for learning.



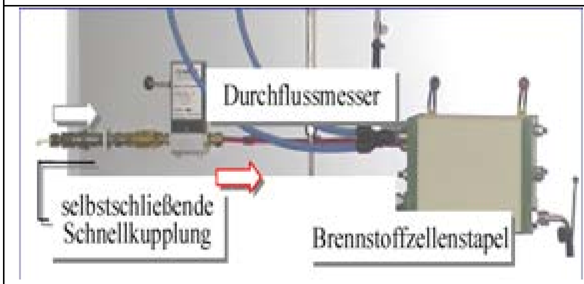
Air supply

Two compressors with membranes feed the air and regulate the rate.



Hydrogen supply

A cylinder and a regulator feed in the hydrogen; with a pressure valve.



Quick coupling

It can lock automatically, and the hydrogen passes a flow metre.

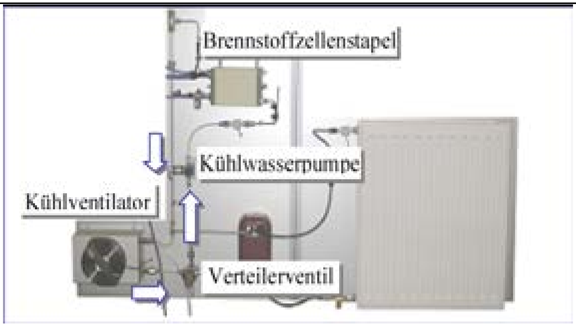
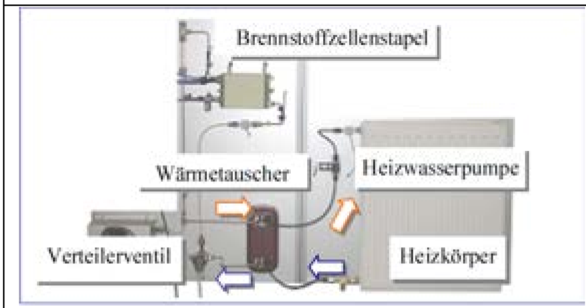
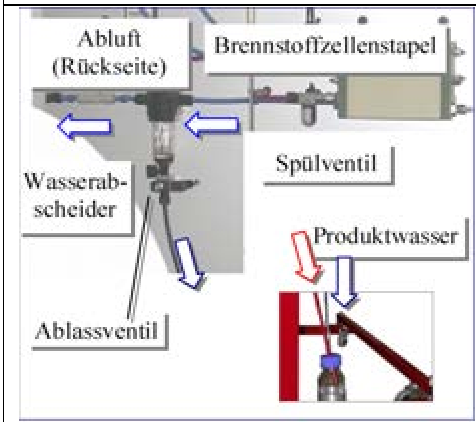
	**Cooling circuit, pump and valve** To prevent the fuel cell from overheat. *There is room for improvement here.*
	**Heat exchanger and distributor** Excess heat is regained as it is passed on to the radiator, by a separate circuit.
	**Flush valve, bleeder valve, separator** Water vapour liquefies in the separator, but needs to exit to avoid a power cut.

Figure A7.1 Auxiliary equipment for a Heliocentris PEM FC *Source: Augsburg (2004)*

The corrosion tests mentioned in HZwei (2012) do not only refer to the main components, but equally to peripheral components, such as tubes, pipes, connectors, fittings, seals, valves and pumps; i.e. the auxiliary equipment demonstrated above. According to HZwei, any equipment coming into contact with de-ionised water is instantly exposed. The tests carried out included immersing the components in 30% H_2O_2 for five days, alternating freezing and defrosting cycles, and heating up to 100°C in deionised water. The results were reported to have shown premature ageing visibly, especially those valves, pipes and connectors that are made of stainless steel. Of course this also has to be taken into account for the recycling equation in the environmental assessment.

Annex 8: Prices of PEM FC and SOFC in 2010 *Source: Staffell & Green (2012)*

	Manufacturer	Electrical Capacity (kW)	Year price was set	Price (2010 USD)†	Subsidy per system‡	Description	Ref.
PEMFC	Eneos	0.7	2011	$24,900	26%	Revised price for the improved Ene-Farm models launched in 2011 and 2012.*	[43, 44]
	Panasonic	0.75	2011	$25,400			[45]
	Toshiba	0.7	2012	$24,200			[46]
	Eneos	0.7	2009	$28,500	43%	Initial sale prices of Ene-Farm systems in Japan.*	[47]
	Panasonic	1	2009	$30,800			[48]
	Toshiba	0.7	2009	$28,500			[47]
	(1 kW class)	–	2010	$52,500	–	*Quoted prices from an anonymous European supplier for a natural-gas fuelled system.*	–
			2008	$238,000			
	GS Fuel Cell, FuelCell Power, HyoSung	1	2010	$75,000	80%	The base price for systems in 2010.	[24]
		1	2008	$107,500	100%	The average price of systems installed in the final year of the Residential Fuel Cell Monitoring Project.	[49, 50]
	Plug Power	5	2002–06	$64,000–86,000	100%	The average purchase price during the US Department of Defense field trials, excluding installation (which averaged $11,000).	[51, 52]
SOFC	Eneos	0.7	2011	$24,900	26%	Initial sale price for the first SOFC-type Ene-Farm system.*	[43, 53]
	Kyocera	0.7	2012	$25,600	25%	Initial sale price for the EneFarm "Type S".*	[54]
			2010	$56,800	21%	Quoted in the METI technology roadmap and by Kyocera during the demonstration project.	[55]
			2008	$89,300	22%		
	CFCL	1.5	2011–12	$27,300	0%	Revised sale prices with 2 year warranty, excluding installation (estimated at $1,000).	[56, 57]
			2010–11	$28,400		Initial sale price, inclusive of installation and 2 years servicing. This price rose to $43,500 for a 5-year contract.	[58]
	Sulzer Hexis	1	2000–05	$72,000	–	The cost of early demonstration systems. The later Galileo model was described as "less costly", but no price was given.	[35]

Annex 9: Comparison of residential fuel cell programmes

	Ene-farm	CALLUX and NIP	Ene.field
Timescales	2010-2015	2008-2015	2012-2017
Countries involved	Japan	Germany	UK, Germany, France, Netherlands, Denmark, Italy , Spain, Austria, Luxemburg, Belgium, Slovenia
Electrical efficiencies	30-35%	30-34%	> 35% by end of trial
System efficiencies	60-80%	80-95%	>85% (LHV)
No. units	>9,000 to date	800 + 1400	960
Unit capacity			0.3-5kW
Type	Integrated system consisting of fuel cell subsystem, peak heater and hot water storage tank. Designed to produce electricity and hot water	Integrated system with fuel cell and peak heater to produce electricity, tap water and supply heat to the home. Storage is a supplementary part of the system	Combination of integrated and separate systems. Storage is a supplementary part of the system.
Technology	PEM and SOFC	PEM and SOFC	HT SOFC, IT SOFC, HT PEM and LT PEM

Source: EUVPP (2013)

Annex 10: Hydrogen storage: Redlich-Kwong Equation of State

Lin suggests to apply the Redlich-Kwong Equation of State to determine 'the molar volume of hydrogen gas under certain conditions, and to compare the coefficient of the corresponding ideal gas volume. V_m is the volume per mole, R the ideal gas constant, P pressure, T_C critical temperature and P_C critical pressure, and a and b empirical constants given by the equation of state. The value of the ideal gas, right-hand side is 0.101 l/mol, while the left-hand side for the hydrogen gas worked out to be 0.117 l/mol. 'The 16% difference is the work put in to compress the hydrogen'; Lin 1999.

$$\left[\mathbf{P} + \mathbf{a} / \mathbf{V_m} (\mathbf{V_m} + \mathbf{b})\, \mathbf{T}^{1/2} \right] * (\mathbf{V_m} - \mathbf{b}) = \mathbf{R} * \mathbf{T} \qquad (21)$$

(given constant a) $a = 0.42748 * (R^2 * T_C^{2.5} / P_C)$

(given constant b) $b = 0.08664 * (R * T_C / P_C)$

0.117 l/mol > 0.101 l/mol

Annex 11: H_2-car and hydrogen filling stations

To fill H_2-gas is similar to CNG. But the properties are different, a CNG-car requires 15 kg and the H_2-car 5 kg, a CNG-car runs by combustion and the H_2-car electrically. Hydrogen supplied to the fuel cell on-board provides e-mobility with a longer range of currently up to 650 km. In a current fuel cell-Hyundai, Hyundai (2013), two tanks (40 l in the front, and 104 l in the rear) with 80 mm thickness hold a total 5.6 kg at 700 bar.

The electrolyser needs 55.55 kWh and 9.25 h to produce 1 kg H_2 (311 kWh and 52 h for the whole tank). As H_2 has a low density (0.080 kg/m³), it needs to be compressed.

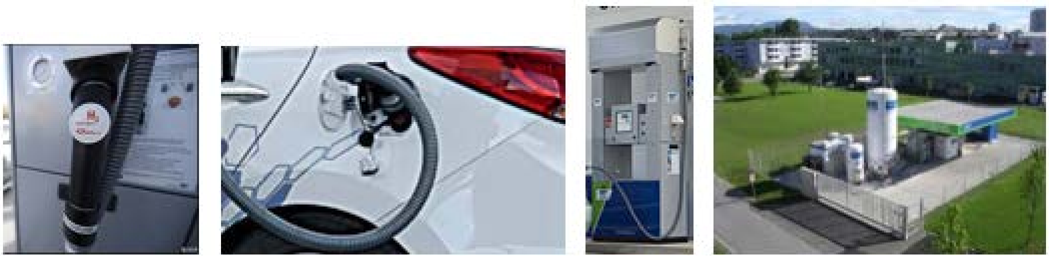


Figure A11.1 Filling H_2-gas *Source: Hyundai, OMV, HyCentA (all 2013)*

The Institute of Innovative Technology in Bolzano, South Tyrol is constructing a filling station at the motorway exit "Bolzano-South" with H_2 generated from PV, and the municipality owns 5 hydrogen busses.[7] This will be an option to fill the car not too far from Innsbruck. In addition, the HyCentA-station from Joanneum and TU Graz is for

[7] Meeting and discussion with Dr. Clauser and Dr. Rinner of IIT in Bolzano on 25.1.2013, after visiting the Klimahouse-fair.

the Eastern part of Austria, as well as the OMV-station in Floridsdorf. The latter is an existing petrol station, and since 27 October 2012 they supply H_2 at 0.900 €/g.[8] At the Greenexpo on 19.4.2013 representatives of OMV explained that currently the H_2 is obtained from steam reforming and in future will be gained from renewables.[9]

Annex 12: Weather parametres of Innsbruck in detail

a) Solar radiation

AEE Intec stated in 2004 that the Sun radiates 219,000 trillion kWh of energy a year (10^{15}). The highest radiation measured in some regions reach 2,200 kWh/m², whereas Austria receives up to 1,400 kWh/m² or less. Innsbruck is favoured with 1,100 kWh/m².

Figure A12.1 gives an impression about where in Austria most of the Sun is collected on horizontal surfaces. Some small pockets in the West even reach above 1,200 kWh/m². Figure A12.2 illustrates how diffuse the sky can be, although rays are absorbed on cloudy days as well, referred to as "Back radiation".

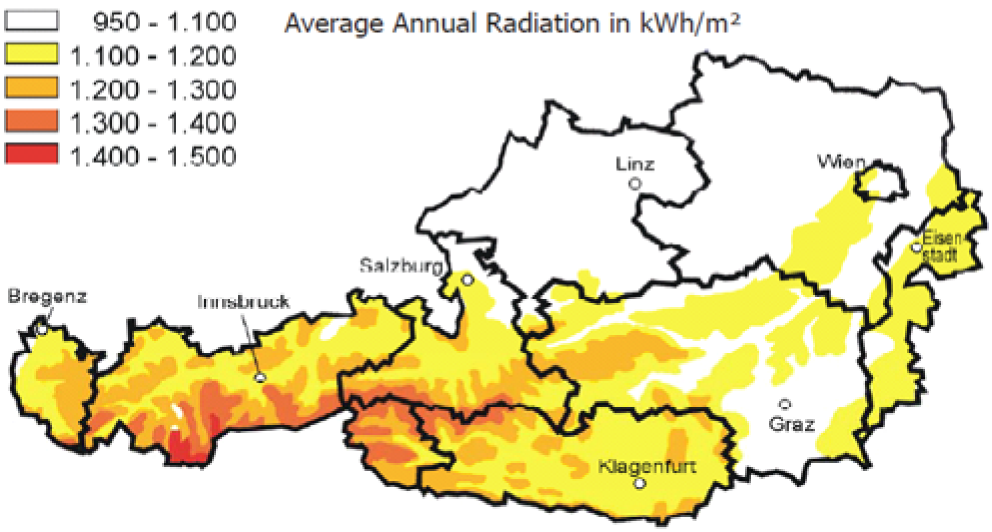


Figure 11: Annual mean long-term total global radiation on a horizontal surface for different regions in Austria in kWh/m².

Figure A12.1 Average annual radiation in kWh/m² in Austria *Source: AEE Intec (2004)*

[8] Article: "Kraftstoff tanken in Kilos", derStandard.at-online, 17.10.2012, 14:21.

[9] *Other projects the persons mentioned included "e-log Biofleet", generating H_2 from biogas from sewage, and "Power2Gas", where the excess energy from eg. windparks is electrolysed into hydrogen and added to increase the volume of natural gas.*

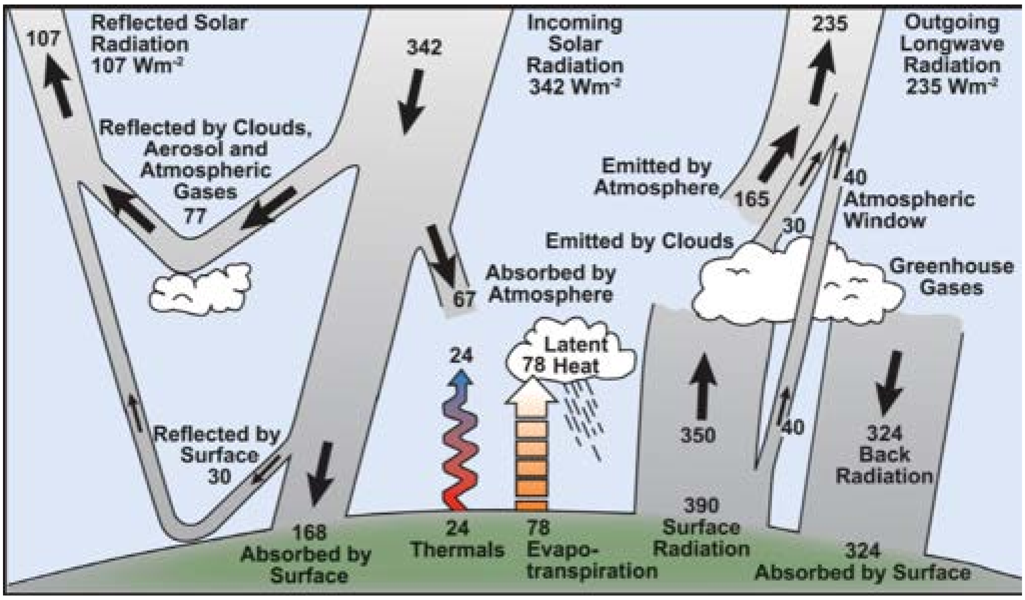


Figure A12.2 Solar radiation and diffusion of sky *Source: Nakicenovic/Haas (2010)*

b) Solar hours per month

According to Statistik Austria, monthly hours of Sun amounted to 1,954 hours in 2012. From their data an average of the last five years was taken, and resulted in 1,946 hours. In this figure are also included 2003, which recorded a high as 2,304 hours, and the year 1912, with as low as 1,416 hours. For the record, 1,900 hours per year are taken; Statistik Austria (2013).

Figure A12.3 is a an Excel-generated graph based on the monthly Sun hours of the years 2012, 2011, 2010, 2009, 2009, 2003 and 1912 from Statistik Austria. The black line is the average of these monthly figures for the seven reference years. The values can be found in the Appendix, as well as four additional figures on Sun hours in Tyrol.

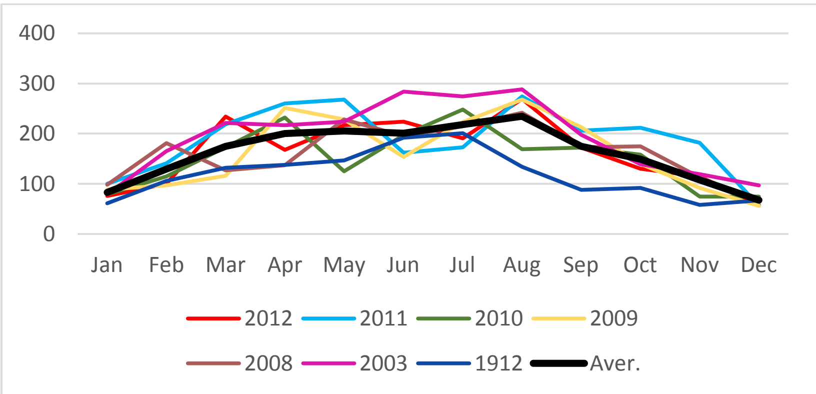


Figure A12.3 Sunshine hours for seven reference years *Source: Statistik Austria (2013)*

In the first scenario, sufficient sunrays enable the PV to supply energy straight away. This Section will look at the dimensioning of the PV in order to assess the whole year's PV yield according to energy needs, and the possibility to store, in the next Section.

Portioning PV depends on solar hours and angles of insolation, radiance and diffusion. In Figure A12.4 angles of insolation at 47° latitude North (about that of Innsbruck) are shown on the left-hand scale. At noon they are highest between 21 May and 21 July, above 60°, and lowest on 21 December, at below 20°; if the PV modules face 0° South. On the right-hand side the corresponding fixed object is displayed, but does not take into account any obstructions by other buildings that would cause a temporary shadow.

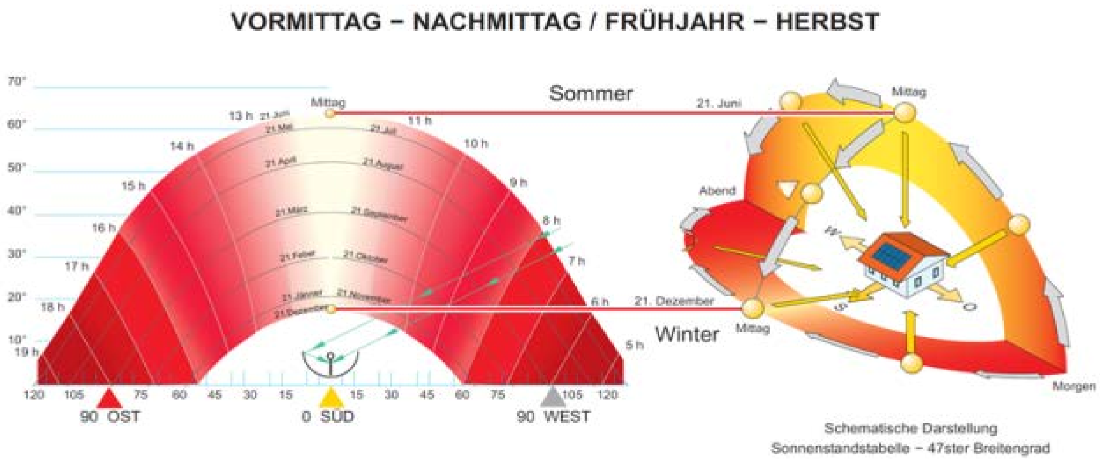


Figure A12.4 Annual solar altitude at 47° latitude North on a fixed object *Source: Solarfocus/Hober (2013)*

c) Heating degree days

Heating 2degree day measurements taken from Innsbruck statistics amounted to the figures shown below in Table A12.5, whereby these area calendar years and not the 12/20 system. Though HDD is not taken in this paper as a basis to calculate heat load, the significance of these values is to obtain an estimate. Also, 1994 was as a very warm year with only 2,986 HDD, and 1940 a very cold year with 3,999 HDD.

	2012	**2011**	**2010**	**2009**	**2008**	**1994**	**1940**	**Average**
HDD	3,342	3,113	3,331	3,258	3,154	2,986	3,999	**3,311**
Average °C	9.8	10.4	9.5	10.1	10.2	10.8	6.9	**9.7**

Table A12.5 HDD for seven reference years in Innsbruck *Source: Histalp (2013)*

d) Temperature

Figure A12.6 shows the mean temperatures of the last 50 years for Innsbruck, at the Airport Kranebitten in the West, which appears to indicate that they have been on the rise for the last half Century. This indicates that HDD in Innsbruck may become less overall if th trend continues. As a current mean annual temperature 9.7°C are taken.

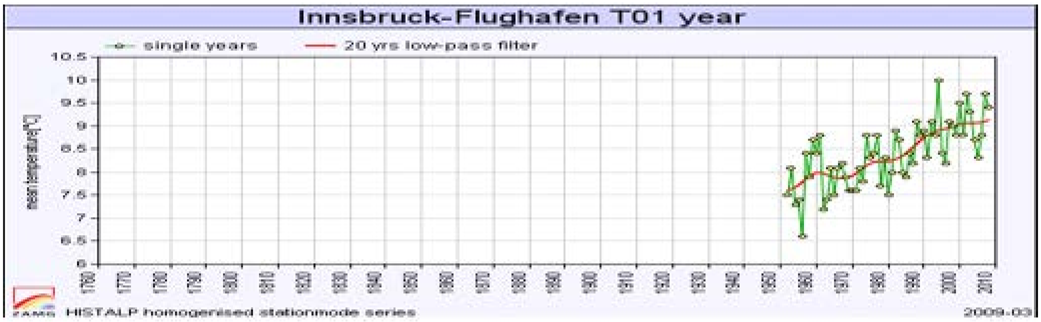


Figure A12.6 Mean temperatures at Innsbruck Airport from 1952 to 2009 *Source: Histalp (2013)*

e) Ground water temperature

What is significant for the buffer tank is the ground water temperature. Tyrol statistics measures in Rum (a Northern suburb of Innsbruck) a ground water temperature of 11° in April and 13°C in December. Fluctuations have been considered in the calculations. The melting Winter snow takes time to flow into the underground and cool the water.

f) Precipitation

Innsbruck statistics measured precipitation in the last 150 years. The most was in 1999 at 1,200 mm, and least in 1866 at 534 mm. An estimate of 900 mm is considered here. Precipitation though blocking the sunrays, but also washes the dust of the PV panels.

Figure A12.7 shows the last 150 years of precipitation in Innsbruck with no clear trend.

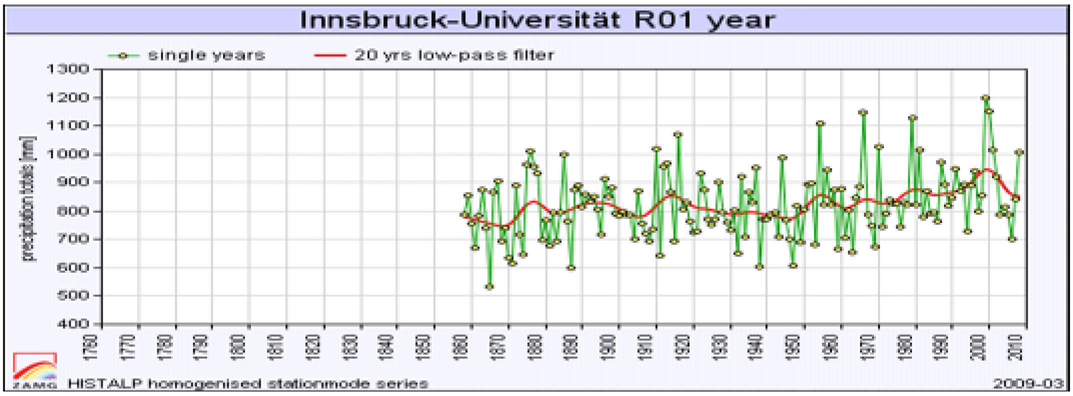


Figure A12.7 Precipitation since 1860 at Innsbruck University *Source: Histalp (2013)*

g) Other general information as background

In similar way snow can be an obstruction to the PV. 500 cm are taken as an estimate. Mountains around Innsbruck (such as the Patscherkofel) carry wind speeds of up to 200 km/h. More significant is the föhn (chinook wind) with sudden temperature drops and rises. In downtown Innsbruck the highest wind speeds measured were 120 km/h. Mean air pressure measured at Innsbruck University since 1830 has remained between 942 and 949 hPa to date; a mean value of 946 hPa will be taken (equal to 710 mmHg). An annual average of 70.4% is recorded by the World Meteorological Organisation. Last not least, fine particles have been debated frequently in recent times. The readings vary by location and daytime; 100 micro grams (10^{-6} gram) is a cautious estimate. According to the City Council of Innsbruck, too high levels of fine particles were measured on 46 days in 2011; mostly between November and March. Also, 41% of fine particles are due fire in buildings, 26% to traffic and the rest from the industry.

h) City of Innsbruck

Innsbruck as the location was chosen for personal reasons; as my Family-in-law is from there.

Figure A12.8 depicts the solar potential on a per roof-basis by kWh per year. The location of the small and medium systems will be in the Western part of Innsbruck.

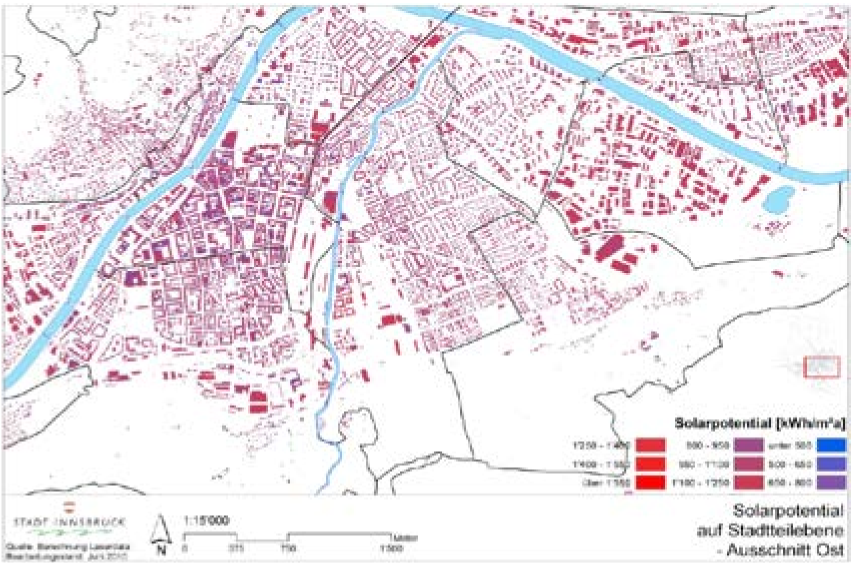


Figure A12.8 Solar potential in Innsbruck in kWh/m²/a *Source: Innsbruck, Environment Council (2011)*

Annex 13: Several units are summarised in Table A13.1

Table A13.1 SI (International System of Units) relating to electrochemistry *Source: Dobler (2003)*

Scientist	**Unit**	**Purpose**	**Function of …**	**Alternative function of …**
Newton	N	force	1 kg * m / s^2	
Pascal	Pa	pressure	1 N / m^2	1 kg / (m * s^2)
Watt	W	power	1 N * m / s	1 kg * m^2 / s^3
Coulomb	C	electric charge	6.24 * 10^{18} electrons	
Volt(a)	V	electric potential	1 kg * m^2 / (C * s^2)	1 N * m / C
Avogadro	N_A	atoms per mole	6.02 * 10^{23} atoms	
Ampère	A	electric current	1 C / s	
Faraday	F	electron charge p. mole	9.6485 * 10^4 C	1.602 * 10^{-19} * N_A
Joule	J	energy	1 kg * m^2 / s^2 = N * m	1 Pa * m^3 = W * s = C * V
Ohm	Ω	electrical resistance	V / A = m^2 * kg / (s * c^2)	J / (s * A^2) = J * s / C^2 = s / F

Annex 14: Additional fuel cell equations

a) Structure of a water molecule

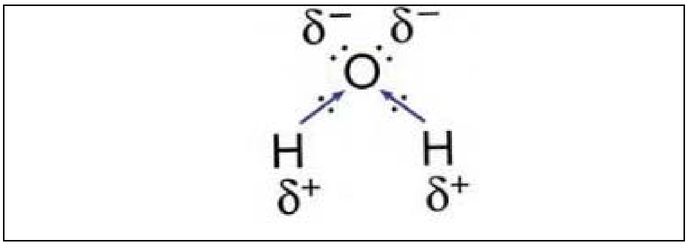


Figure A14.1 A water molecule *Source: "Chemistry in Context" (1997)*

b) Molar mass of hydrogen, oxygen and water

1 mole of Hydrogen atoms (Avogadro's number 6.0221367 x 10^{23}) weighs 1 gram. Due to two sporadic isotopes, deuterium (^2H) and tritium (^3H) the exact measure is 1.00794g. Two moles hydrogen (2.01588 g/mol) and one mole oxygen at 15.9994g result in one mole water with a molar mass of 18.01528 g, two moles H_2O are 36 g; Larminie (2003).

$$\mathbf{H_2 + \tfrac{1}{2}\, O_2 = H_2O} \qquad (22)$$

$$2 * 1.00794g + 15.9994g = 18.01528g$$

(resp. two moles of water) $2\,H_2 + O_2 = 2\,H_2O$

c) Anode and cathode [10]

Electrodes are mainly made of platinum (Pt). Hydrogen molecules enter the anode. The protons pass through the membrane, the electrons leave the cell, give their power

[10] From the Greek: "ἄνοδος" (anodos) means "ascend", and κάθοδος (kathodos) being "descend" resp.

and re-enter at the cathode. Redox-equations often take into account two molecules; Walkowiak (2005).

(oxidation) $$\mathbf{2\,H_2 = 4\,H^+ + 4\,e^-} \quad (23)$$
(reduction) $$\underline{\mathbf{O_2 + 4\,H^+ + 4\,e^- = 2\,H_2O}} \quad (24)$$
(redox-reaction) $$\mathbf{2\,H_{2(g)} + O_{2(g)} = 2\,H_2O_{(l)}} \quad (25)$$

When the gases react energy is being released; hydrogen is oxidised, oxygen reduced. Due to the proton exchange membrane the protons permeate in a controlled manner. Thermodynamic formulae are found in Nave (2013) and Kurzweil (2013). According to them, H_2-gas does not have it's own enthalpy, but by the addition of H^+-protons and the resulting creation of H_2O-molecules, enthalpy can be traced and quantified.

d) Fuel consumption

These four points n)-q) were studied in Walkowiak (2005) and cross-checked in Larminie (2003). At standard temperature and pressure 1 m³ H_2 weighs 0.084 kg (*air weighs 1.2 kg/m³*). To answer at what rate hydrogen is being consumed by the fuel cell:

$$\boldsymbol{\mu_{H2} = I * n / (2\,e^- * F)}\text{ in mol/s} \quad (26)$$
$$\mu_{H2} = (P_{El} / E_{act}) * (1 / 2 * F)\text{ in mol/s}$$
(convert to kg) $$\mu_{H2} = 2.02\text{x}10^{-3} * (P_{El} / E_{act}) * (1 / 2 * F)\text{ in kg/s}$$
$$\mu_{H2} = 1.05\text{x}10^{-8} * (P_{El} / E_{act})\text{ in kg/s}$$
$$\mu_{H2} = 3.49\text{x}10^{-5}\text{ kg/s}$$

e) Oxygen usage

There are two ways to assess the O_2 consumed by a fuel cell; pure versus from the air. The number of molecules are n, and the membrane current is I measured in ampére. Larminie points out the stoichiometry of oxygen in air relates to the air-fuel ratio, i.e. at 21% O_2 in air the λ is 1. If the concentration is richer, then $1 < \lambda$, or if less, then $1 > \lambda$.

(pure O_2) $$\boldsymbol{\mu_{O2} = I * n / (4\,e^- * F)}\text{ in mol/s} \quad (27)$$
$$\mu_{O2} = (P_{El} / E_{act}) * (1 / 4 * F)\text{ in mol/s}$$
(convert to kg) $$\mu_{O2} = 0.032 * (P_{El} / E_{act}) * (1 / 4 * F)\text{ in kg/s}$$
$$\mu_{O2} = 8.29\text{x}10^{-8} * (P_{El} / E_{act})\text{ in kg/s}$$
$$\mu_{O2} = 27.63\text{x}10^{-5}\text{ in kg/s}$$

(from air) $$\mu_{Air} = (28.97\text{x}10^{-3} / 0.21) * (P_{El}/ E_{act}) * (1 / 4 * F)\text{ in kg/s} \quad (28)$$
$$\mu_{Air} = 3.57\text{x}10^{-7} * (P_{El}/ E_{act})\text{ in kg/s}$$
$$\mu_{Air} = 133.33\text{x}10^{-5}\text{ in kg/s}$$

f) Water

The oxidation of H_2 produces a molecule of water for every two electrons δ^- added.

$$\Pi_{H2O} = (P_{El} / E_{act}) / (2 e^- * F) \text{ in mol/s} \quad (29)$$

(convert to kg) $\Pi_{H2O} = 18.02x10^{-3} * (P_{El} / E_{act}) / (2 * F)$ in kg/s

$\Pi_{H2O} = 9.34x10^{-8} * 2{,}000W / 0.6V$

$\Pi_{H2O} = 31.13x10^{-5}$ kg/s

(and in 1 hour/3,600 seconds) $\Pi_{H2O} = 1.12$ kg/h

Annex 15: Electrolysis

The formulae are based on Kurzweil (2013), Larminie (2003) and Nave (2013); some sources treating fuel cells did not include water electrolysis as they centred on the reforming of natural gas. The electric current splits the water molecules (endothermic). Oxygen forms at the anode and is released into the atmosphere, or accumulated. H^+-protons travel through the membrane to the cathode. Electrons move in the circuit and return to form H_2 gas.

(cathode) $2 H_2O = O_2 + 4 H^+ 4 e^-$ (30)

(anode) $\underline{4 H^+ 4 e^- = 2 H_2}$ (31)

(total reaction) $2 H_2O_{(l)} = 2 H_{2(g)} + O_{2(g)}$ (32)

In thermodynamic terms, energy is now put in, to break up H_2O; the figure is positive.

$$\Delta G = \Delta H - T\Delta S \quad (33)$$

$\Delta G = 285.83$ kJ - 48.7 kJ

$\Delta G = 237.13$ kJ

Figure A15.1 shows a ΔG of 237.13 kJ/mol as energy input, and $T\Delta S$ of 48.7 kJ/mol. According to Professor R. Nave of Georgia State University, it is the entropy of the environment that helped to improve the process by providing $T\Delta S$; this is at 298 K.

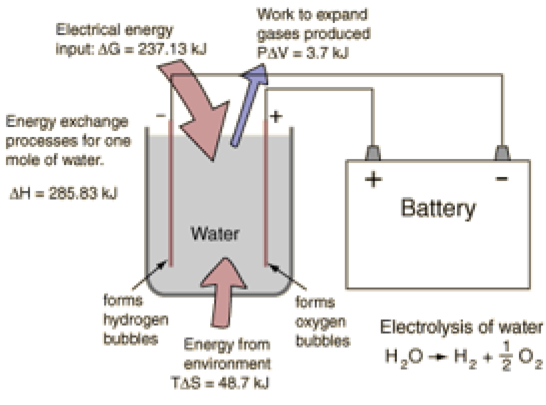


Figure A15.1 Thermodynamics of electrolysis *Source: Nave (2013)*

Annex 16: Water buffer tank

The equation to dimension the water storage is given by Weiss (2012) lecture, where Q_s is the product of volume m, specific heat capacity of water C_p and temperature ΔT. The specific heat capacity of water is 1.16 kWh/m³K. Surplus and discharged warm water and heat (collected from shower, bath, fridge and fuel cell) can be channelled through a heat exchanger, which reduces the energy needed to heat water up to 60°C.

$$\mathbf{Q_{s,\,small} = (m * C_p) * \Delta T} \tag{34}$$
$$Q_s = (0.3 * 1.16) * 48$$
$$Q_s = 16.7 \text{ kWh}$$

Annex 17: Smart metre and the relais relative to energy services demand

$\mathbf{E_{Base}}$: The inverter at 95.9% is calculated here, because this calculation is not about annual quantity as above, but capacity at a given moment. The heat pump requires 1.64 kW el, but only runs the equivalent power of 2 hours per day, for the small system and 5.59 kW el for the medium system resp. The refrigerator, the WIFI and radio clock amount to 200 Watt, resp. 1 kW for medium system; based on various literature.

$$\mathbf{E_{Base,\,sm} = [\mathit{4.1\%}] + (1.64\ kW/24*2) + 0.2\ kW} \tag{35}$$
$$E_{Base} = 13 \text{ kW}*4.1\% + 0.14 \text{ kW} + 0.2 \text{ kW}$$
$$E_{Base} = 0.53 \text{ kW} + 0.34 \text{ kW}$$
$$E_{Base} \approx 0.9 \text{ kW [rounded]}$$

$\mathbf{E_{House}}$: The kitchen has an array of equipment including microwave, kettle, coffee machine and an electric oven, equal to 7 kW in total; imagining it may run in parallel. Household appliances are can be several, including vacuuming and ironing, but are averaged at 1 kW, as they are applied alternatingly. Bathroom-related activities could mean a hair-dryer and one electric shave at the same time, therefore 2 kW are applied.

$$\mathbf{E_{House} = (7 + 1 + 2)\ kW} \tag{36}$$
$$E_{House} = 10 \text{ kW}$$

$\mathbf{E_{Priv}}$: Energy consumption of light has come down a lot but 1,740 Watt is conservative. A computer, a notebook, a printer, TV sets and hobby-items are covered by 2 kW.

$$\mathbf{E_{Priv} = 1.74 + 2\ kW} \tag{37}$$
$$E_{Priv} = 3.74 \text{ kW}$$

$E_{Support}$: This is subject to the management of the pre-programmed smart metre (4 W). Pending availability the short-term storage, i.e. lithium-ion battery, will be charged, so the efficiency is considered, and since it is an accumulator, the last 2% are always lost. The heating rod from DAfi adds another 3 kW, peripheral components such as a circulation pump (120 W), a heat exchanger (60 W; while there are three, they do not run in parallel)[11], as well as modern digital pressure and temperature gauges (20 W).

$$\mathbf{E_{Support} = (3 + 0.12 + 0.06 + 0.02 + [\mathit{5\% + 2\%}]*13\ kWp + 0.004)\ kW} \quad (38)$$
$$E_{Support} = (3.20 + 0.91)\ kW$$
$$E_{Support} = 4.11\ kW$$

E_{Temp}: The smart metre is programmed to allow for washing or charging E-mobility as complete cycles are favoured over interrupted ones, else it will skip this relais. On solar-intense days the electrolyser may run for several hours and produce hydrogen.[12] The washing machine and tumble drier need to be filled and ready to run (2.5 kW). Accumulators, due to a plethora of devices, needs to be included regularly (0.3 kW).

$$\mathbf{E_{Temp}=(2.5+0.3+2+8+11)kW} \quad (39)$$
$$E_{Temp} = 23.8\ kW$$

E_{Guest} : is a novel, but small contingent is relevant to a friend charging an E-bike resp. on the premises of the medium system, the public wishing to charge their E-mobility.

$$\mathbf{E_{Temp} = 2\ kW} \quad (40)$$

E_{Grid}: is the optional feeding-in due to the excess that can neither be stored anymore. It is portioned pretty close to the kW peak of the PV for respective systems; 11 and 45.

Therefore the totals of the above can be written as follows and to be used as a basis:

$$\mathbf{E_{\Sigma} = E_{Base} + E_{House} + E_{Priv} + E_{Support} + E_{Temp} + E_{Guest} + E_{Grid}} \quad (17)$$
$$E_{\Sigma} = (0.9 + 10 + 3.74 + 4.11 + 23.8 + 2 + 11)\ kW$$
$$E_{\Sigma} = 55.55\ kW$$

In conclusion, if all relais of the smart metres could be fully supplied then 55.55 kW for the small system capacity would be required and for the medium system 199.5 kW.

[11] The heat exchanger is useful, it may absorb waste heat from the showers (outflow temperature 35°C), a kitchen sink (50°C), as well as from the fuel cell. This produces gains of approx. 19%; which can be subtracted from the total PV yield requirement.

[12] Historically, one would have washed on those days, when there was enough Sun to hang outside the wet clothes to dry. Warm water from the buffer storage should go straight to the washing machine, and that saves energy heating the water.

Annex 18: Liberalisation of the energy market

When the government liberalises the utility sector. It means more freedom to the public, but causes supply and management of energy to be less organised. In a study by Haas et al (2009), 'excess capacities in a changing structure are decreasing in relation to increasing demand after the liberalisation process has begun. Only when generation capacity falls to the level of the still rising demand, will the construction of new power plants begin [as probably only then at that point in time the need will be felt]. And with the dire consequence that, while price will fall shortly with begin of liberalisation, it will after a while reverse again, and at the advent of new power plants to be built will rise vertically, and be much higher than before'; Haas et al (2009). This suggests that if a liberalised market is unaware or unable to provision for excess capacities, then storing renewable energy may be an alternative to replenish reserves.

The liberalisation of the electricity production market has an influence on the strategy of the utility companies, mainly in it's role as the energy producer and supplier, but also as the transmission grid operator. Utility companies in Austria commonly gear up the hydropower to supply the peaks at noon. With residential PV on the rooftops, this is becoming obsolete. The question arises when the Sun does not shine sometimes. A discussion with Ing. Gerhard Los clarified that utility companies have addressed this in many ways, for example offering guidance to citizens to install renewable energy equipment and feed-in the excess correctly.[13] The feed-in tariff opens new business potential for companies such as MEA Solar, who is a subsidiary of E-Werk Wels. IKB, in Innsbruck, has a subsidiary dealing with contracting. More in Section 4.3.

Hydrogen produced from excess wind energy and reformed to methane has found it's way into the gas grid (heating), which opens up totally new areas for the utility sector. And so the Section on technology and review of processes will close with this thought.

[13] Discussion with Ing. Gerhard Los, Home and energy consultant, Wien Energie Haus one afternoon on 6.5.2013.

Performance of Grid-connected PV

PVGIS estimates of solar electricity generation

Location: 47°16'45" North, 11°22'54" East, Elevation: 785 m a.s.l.,
Solar radiation database used: PVGIS-CMSAF

Nominal power of the PV system: 13.0 kW (crystalline silicon)
Estimated losses due to temperature and low irradiance: 8.0% (using local ambient temperature)
Estimated loss due to angular reflectance effects: 2.8%
Other losses (cables, inverter etc.): 16.0%
Combined PV system losses: 24.9%

	Fixed system: inclination=35 deg., orientation=10 deg.			
Month	**Ed**	**Em**	**Hd**	**Hm**
Jan	23.30	721	2.22	68.9
Feb	32.90	921	3.18	89.2
Mar	42.30	1310	4.24	131
Apr	53.10	1590	5.44	163
May	52.90	1640	5.58	173
Jun	50.70	1520	5.38	162
Jul	51.80	1610	5.55	172
Aug	47.90	1480	5.07	157
Sep	44.30	1330	4.58	137
Oct	36.90	1140	3.71	115
Nov	23.30	698	2.26	67.8
Dec	19.30	599	1.88	58.3
Year	39.90	1210	4.10	125
Total for year		14600		1500

	Vertical axis tracking system inclination=0°			
Month	**Ed**	**Em**	**Hd**	**Hm**
Jan	12.80	396	1.30	40.4
Feb	21.40	599	2.10	58.9
Mar	33.40	1040	3.30	102
Apr	48.10	1440	4.83	145
May	53.30	1650	5.52	171
Jun	53.00	1590	5.55	166
Jul	53.20	1650	5.61	174
Aug	45.10	1400	4.70	146
Sep	36.50	1100	3.73	112
Oct	25.20	783	2.56	79.3
Nov	13.60	407	1.38	41.5
Dec	10.80	335	1.14	35.3
Year	33.90	1030	3.48	106
Total for year		12400		1270

	Inclined axis tracking system inclination=0°			
Month	**Ed**	**Em**	**Hd**	**Hm**
Jan	17.80	553	1.69	52.3
Feb	30.20	844	2.86	80.0
Mar	44.70	1390	4.40	136
Apr	62.40	1870	6.29	189
May	64.90	2010	6.79	210
Jun	62.70	1880	6.61	198
Jul	63.60	1970	6.76	210
Aug	57.30	1780	5.98	185
Sep	49.30	1480	4.98	149
Oct	35.30	1090	3.48	108
Nov	18.80	563	1.80	54.0
Dec	14.30	443	1.38	42.8
Year	43.50	1320	4.42	135
Total for year		15900		1610

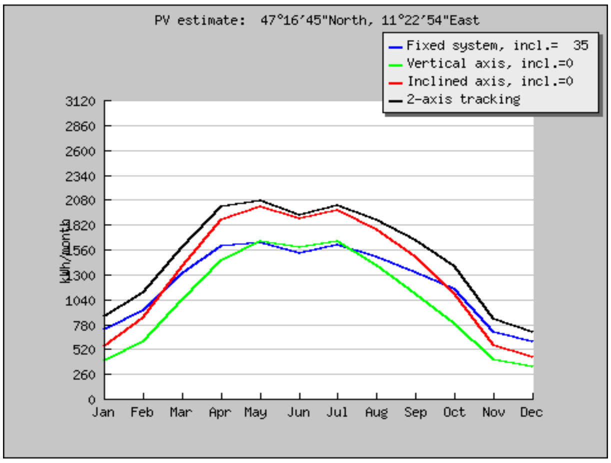
	2-axis tracking system			
Month	**Ed**	**Em**	**Hd**	**Hm**
Jan	27.80	861	2.71	84.1
Feb	39.60	1110	3.92	110
Mar	51.10	1580	5.21	161
Apr	66.80	2000	6.86	206
May	66.90	2080	7.07	219
Jun	64.10	1920	6.79	204
Jul	65.30	2020	6.99	217
Aug	60.50	1880	6.39	198
Sep	55.40	1660	5.73	172
Oct	44.90	1390	4.56	142
Nov	27.70	830	2.74	82.2
Dec	22.40	694	2.23	69.2
Year	49.40	1500	5.11	155
Total for year		18000		1860

Ed: Average daily electricity production from the given system (kWh)

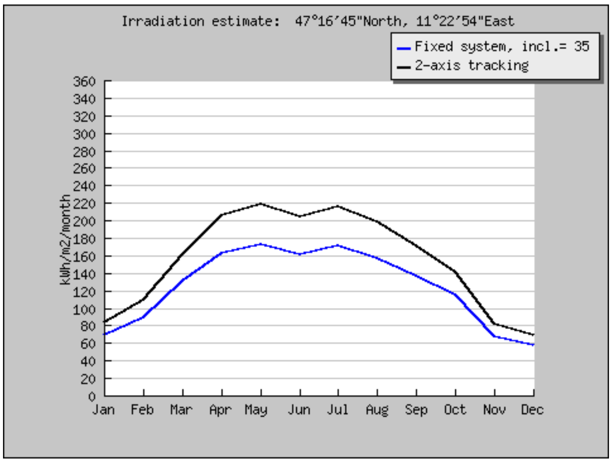
Em: Average monthly electricity production from the given system (kWh)

Hd: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m2)

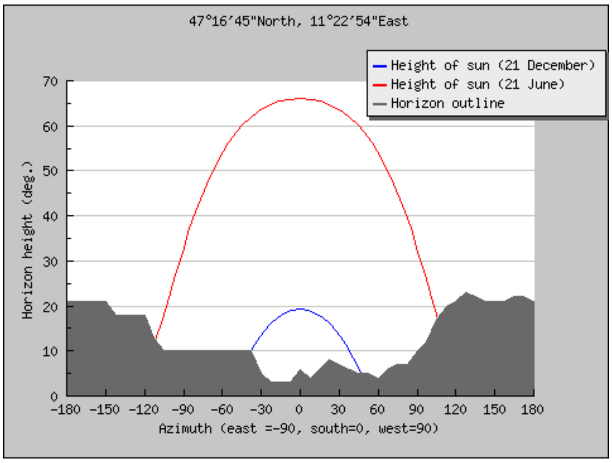
Hm: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m2)



Monthly energy output from fixed-angle PV system



Monthly in-plane irradiation for fixed angle



Outline of horizon with sun path for winter and summer solstice